New Results from Belle

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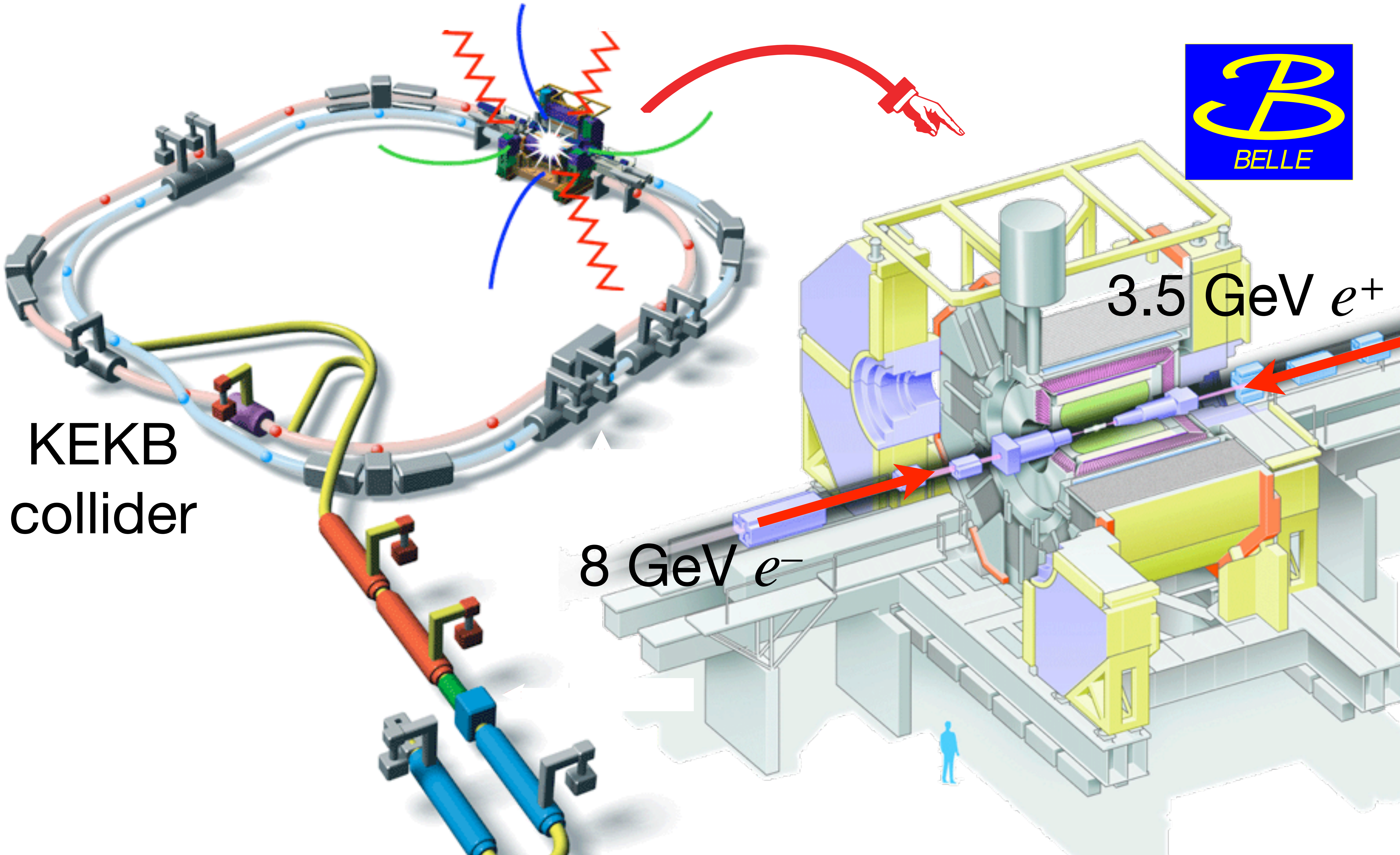
on behalf of the Belle collaboration

BELLE

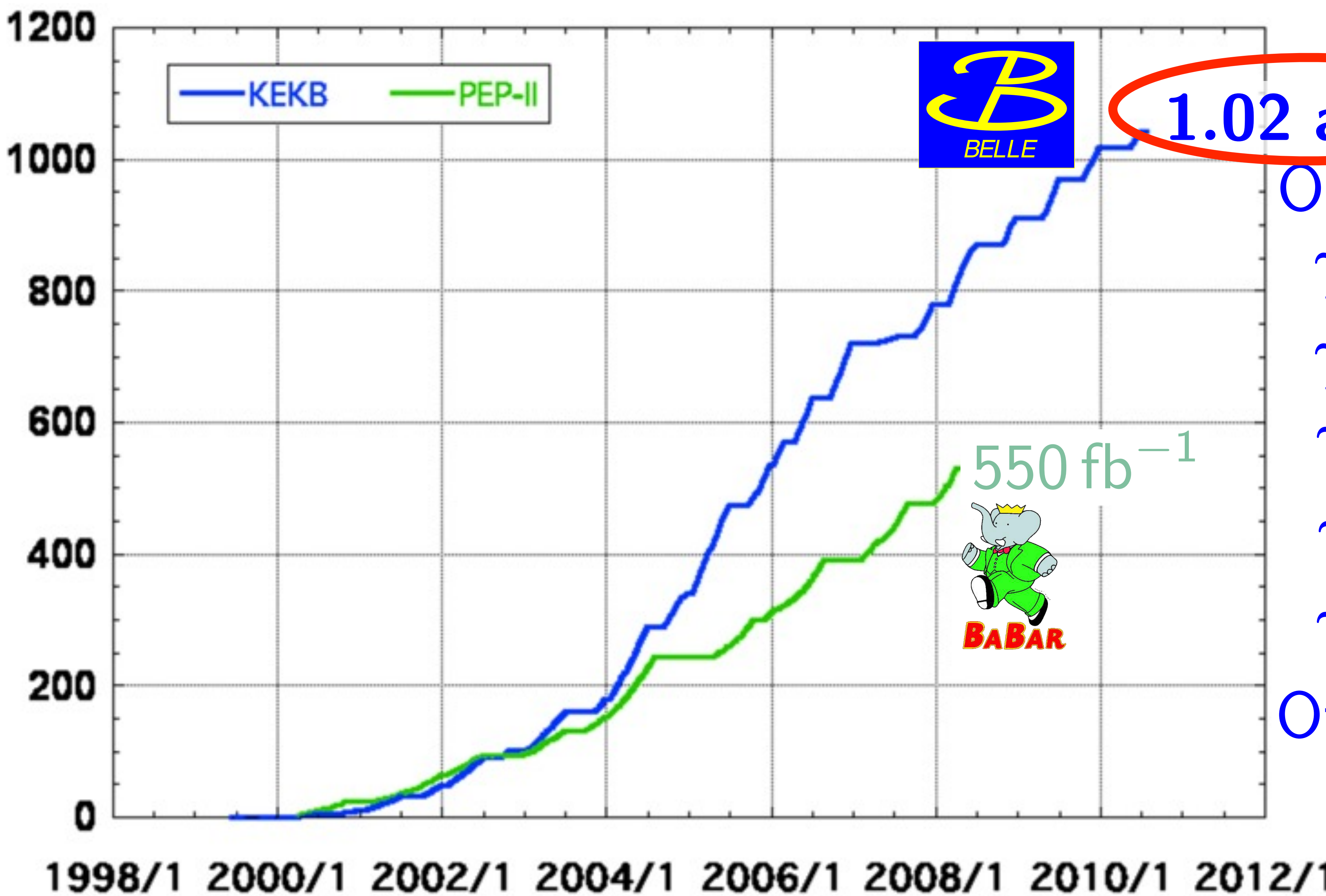
XVI Lomonosov Conference on Elementary Particle Physics *August 2013*

KEK B Factory and Belle: 1999–2010



$$c\bar{c},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow \boldsymbol{e^+e^-} \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Integrated luminosity at the B factories



On resonance:

- $\Upsilon(5S)$: 121 fb^{-1}
- $\Upsilon(4S)$: 711 fb^{-1}
- $\Upsilon(3S)$: 3 fb^{-1}
- $\Upsilon(2S)$: 25 fb^{-1}
- $\Upsilon(1S)$: 6 fb^{-1}

Off resonance/scan: 155 fb^{-1}

KEKB instantaneous luminosity: $\mathcal{L} = 2.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Belle physics output (compiled by Simon Eidelman)

	50-99	100-199	200-299	300-399	400-499	>500	Total
# citations ➡	50-99	100-199	200-299	300-399	400-499	>500	Total
# papers ➡	64	37	10	2	–	2	115

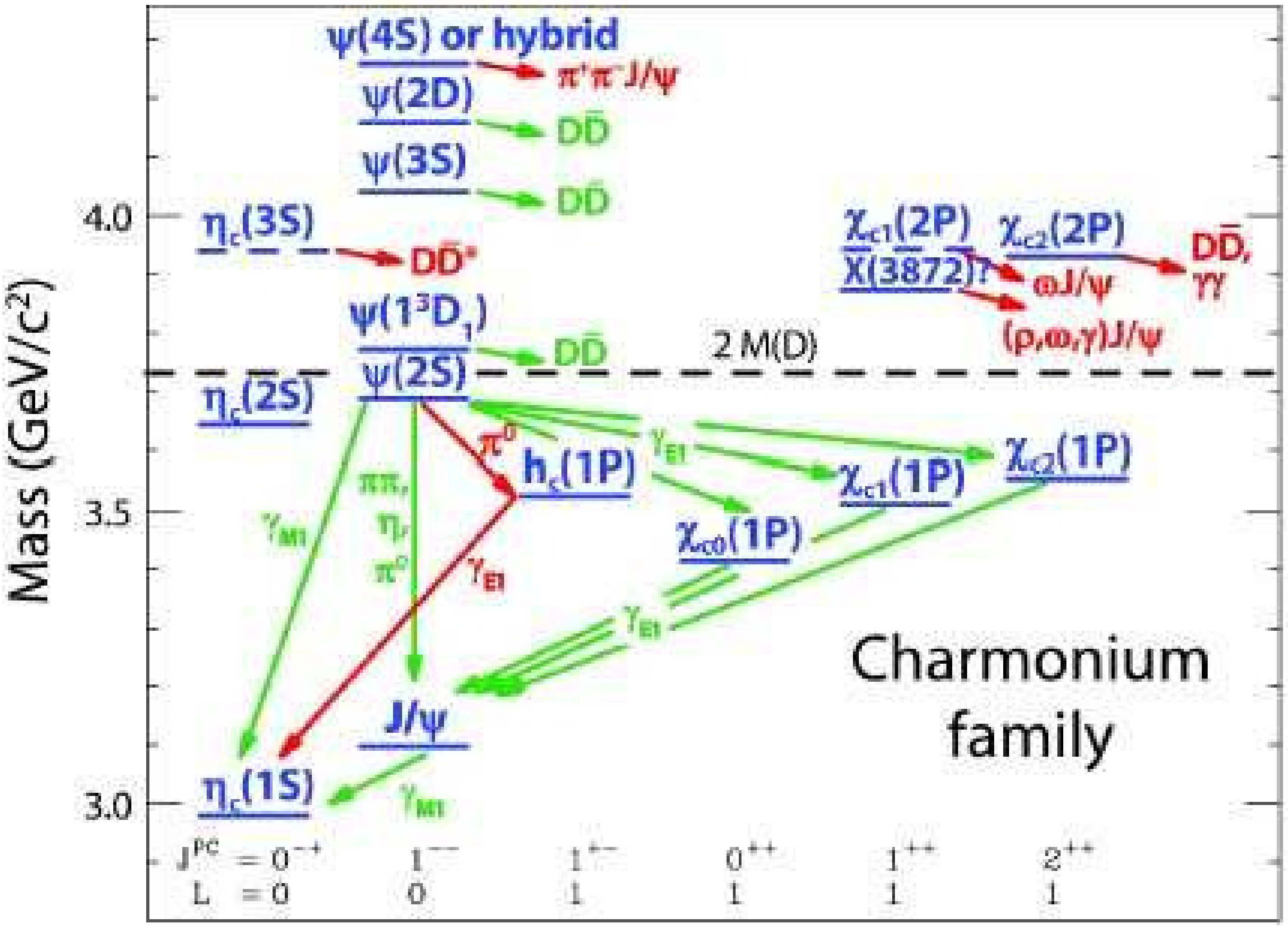
N	Title	Year	Cites
1	X(3872)	2003	739
2	Large CPV	2001	618
3	$B \to X_s \gamma$	2001	381
4	CP in $B^0 \bar{B}^0$	2002	326
5	D0 mixing	2007	292
6	Y(3945)	2005	290
7	$B \to \tau\nu$	2006	277
8	$2c\bar{c}$	2002	272
9	$b \to s\gamma$	2004	265
10	$D_s^*(2317)$, $D_{s1}(2460)$	2003	258
11	D^{**}	2004	249
12	Z(4430)	2008	235
13	D_{sJ}	2006	221
14	$X(3940)$ in $2c\bar{c}$	2007	204

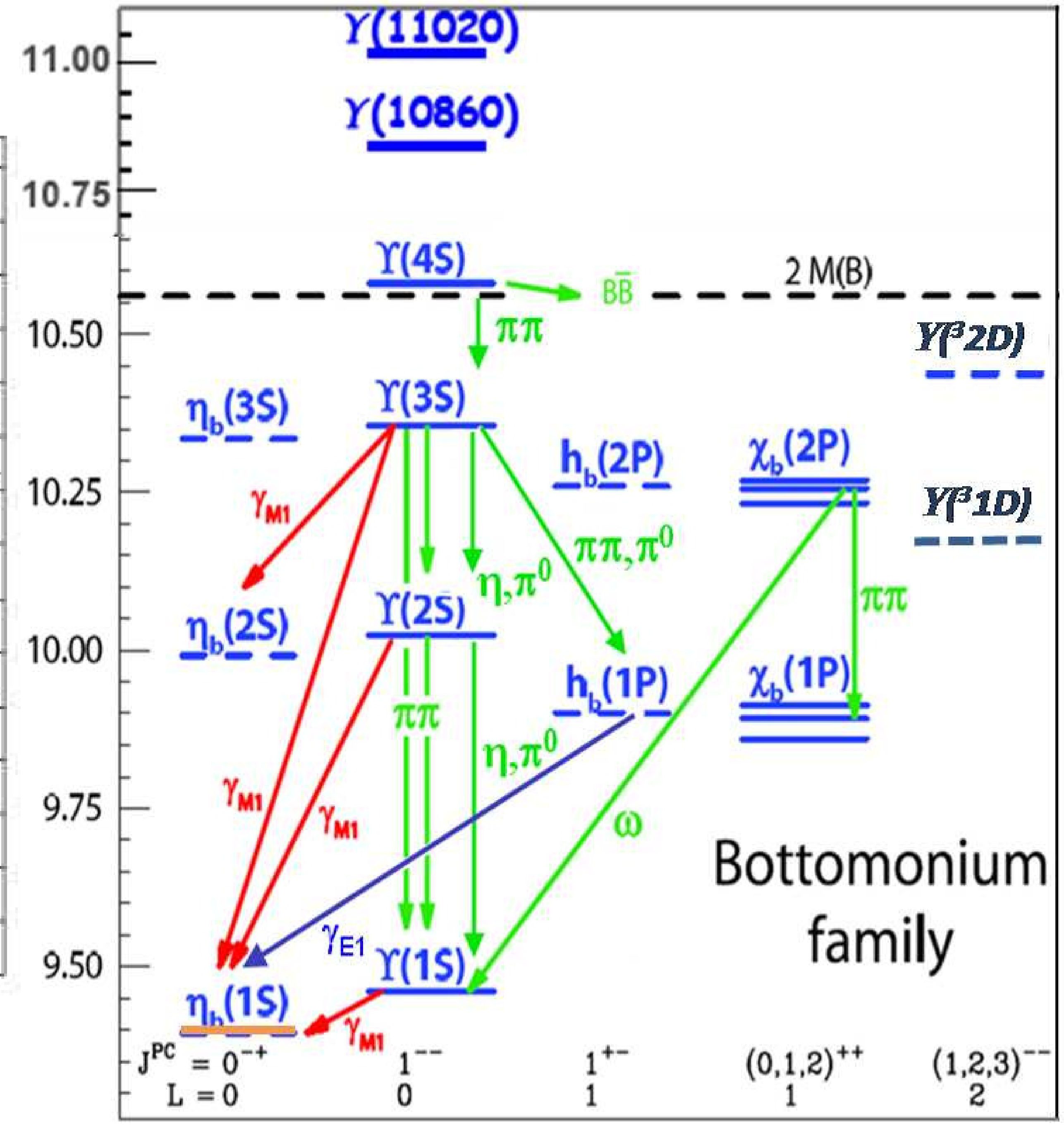
growing at ≈100/year

375 papers published plus ≈30/year

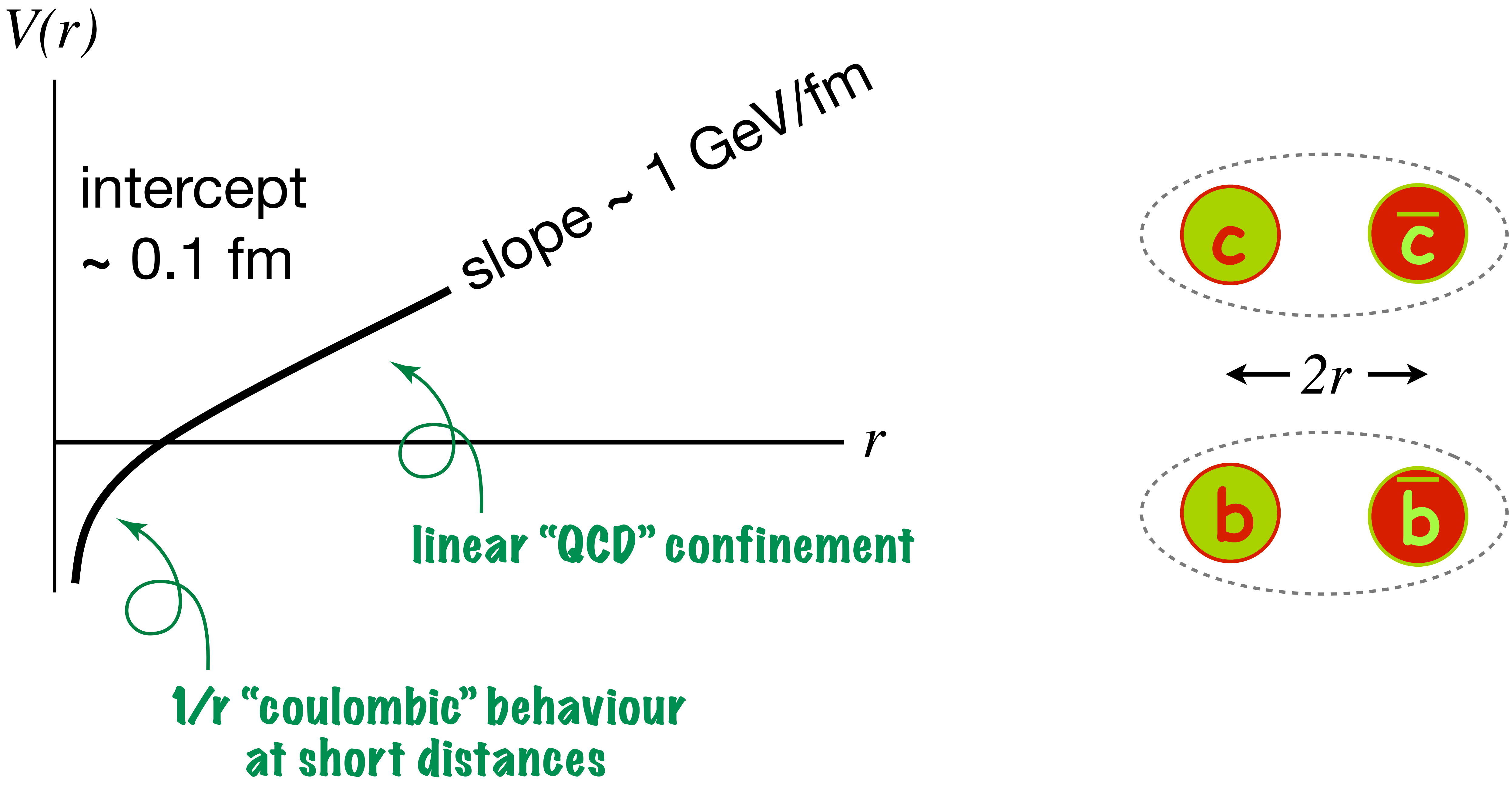
Charmonium(-like) and bottomonium(-like) states

Heavy-quark onia ($q\bar{q}$) are great testbeds for QCD



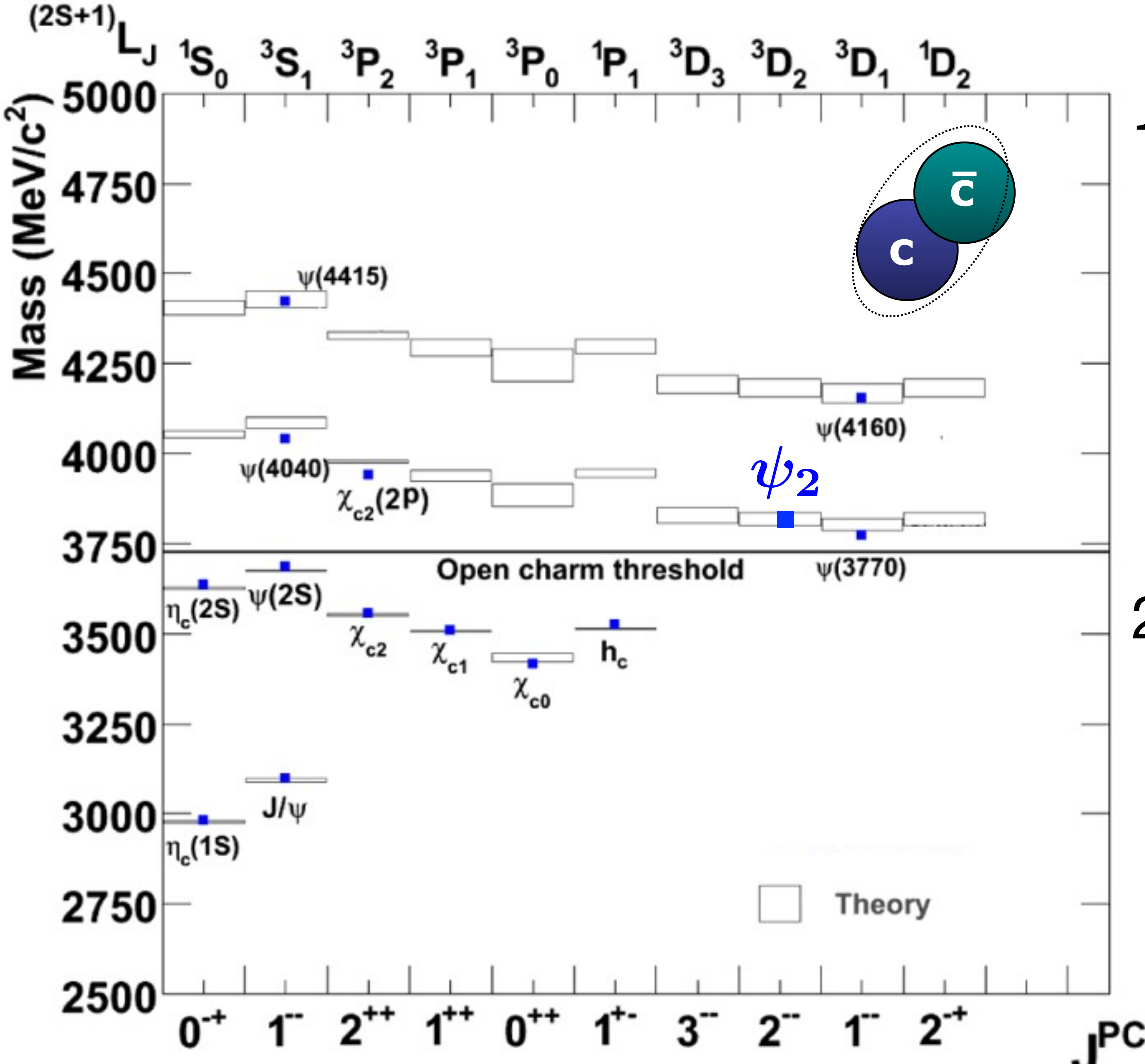


The "Cornell" potential is a useful simple model for charmonium and bottomonium.



Also: other QCD-inspired models and lattice QCD

All states below open-charm threshold have been observed ■ and match the predictions.



1974–1980:

$J/\psi,\ \psi(2S),\ \eta_c,$
$\chi_{c0},\ \chi_{c1},\ \chi_{c2},$
$\psi(3770),\ \psi(4040),$
$\psi(4160),\ \psi(4415)$

2002–now:

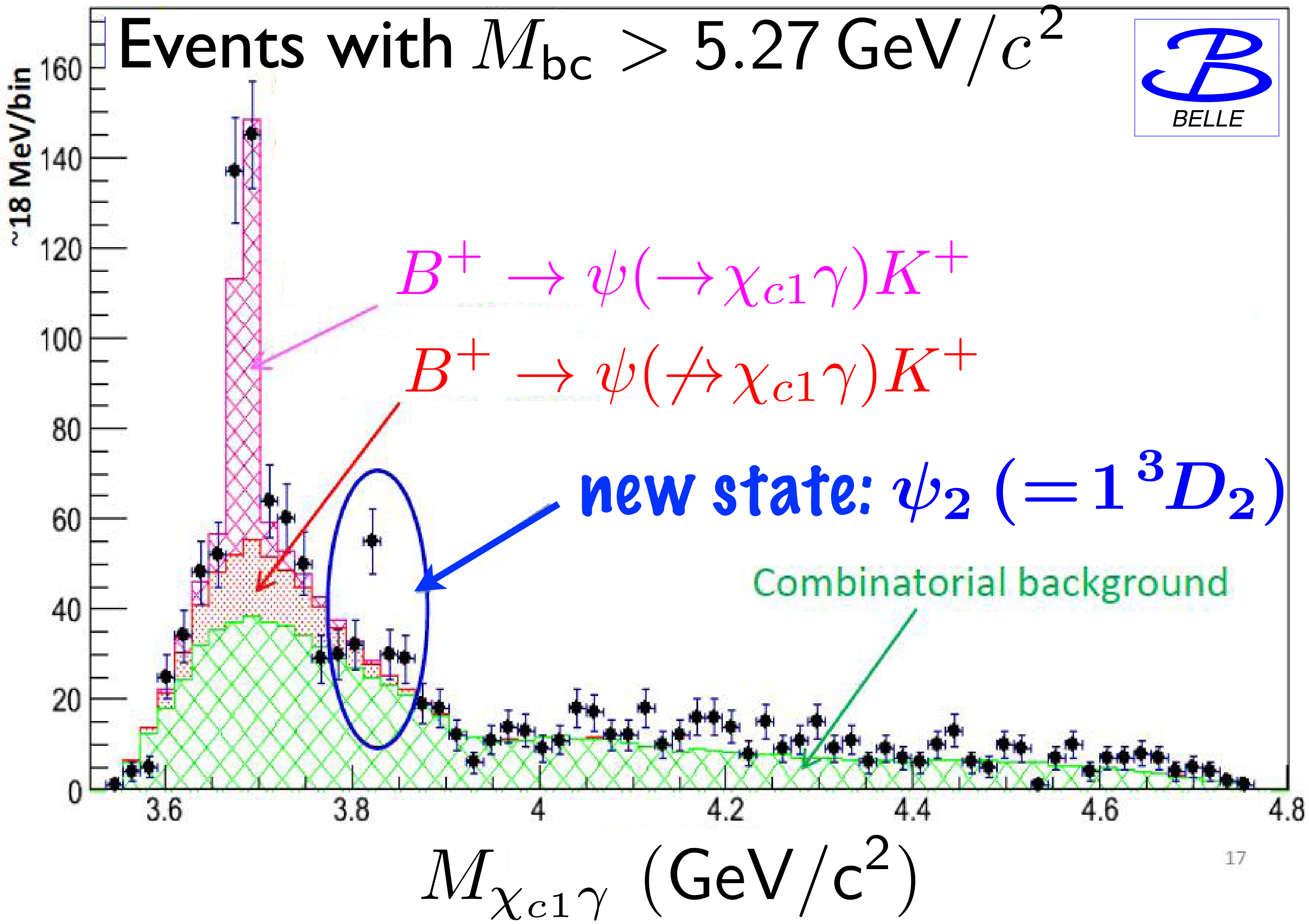
$\eta_c(2S),\ h_c,$
$\chi_{c2}(2P),\ \boldsymbol{\psi_2}$

new!

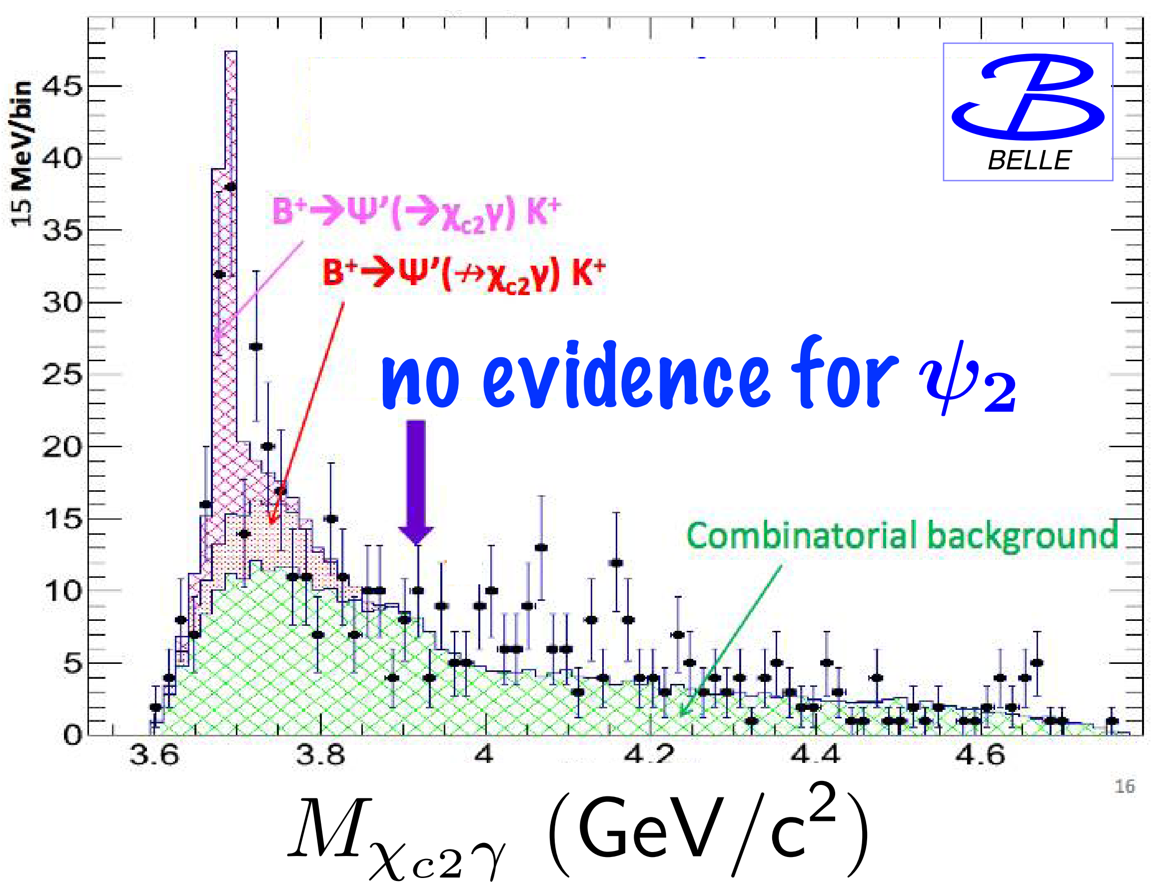
Another $c\bar{c}$ state above open-charm threshold has been observed by Belle in $B \to K(\chi_{c1}\gamma)$

... but not in $B \to K(\chi_{c2}\gamma)$

PRL 111, 032001 (2013)



772M $B\bar{B}$ events



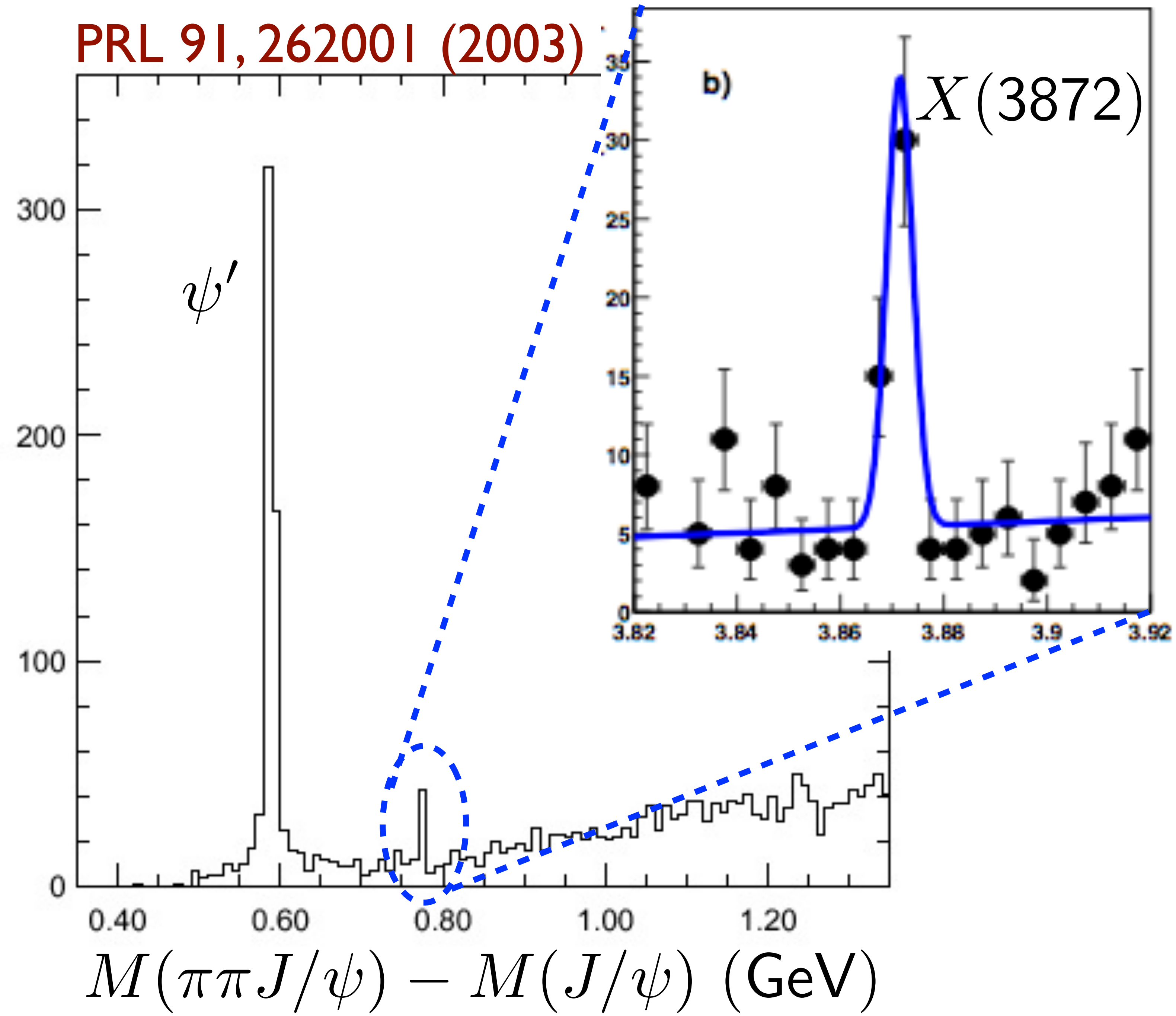
$M = 3823.1 \pm 1.8 \pm 0.7$ MeV/c^2 $\quad (\mathcal{S} = 3.8\sigma)$

... consistent with prediction for $1\,^3D_2$

And now for the exotica ...

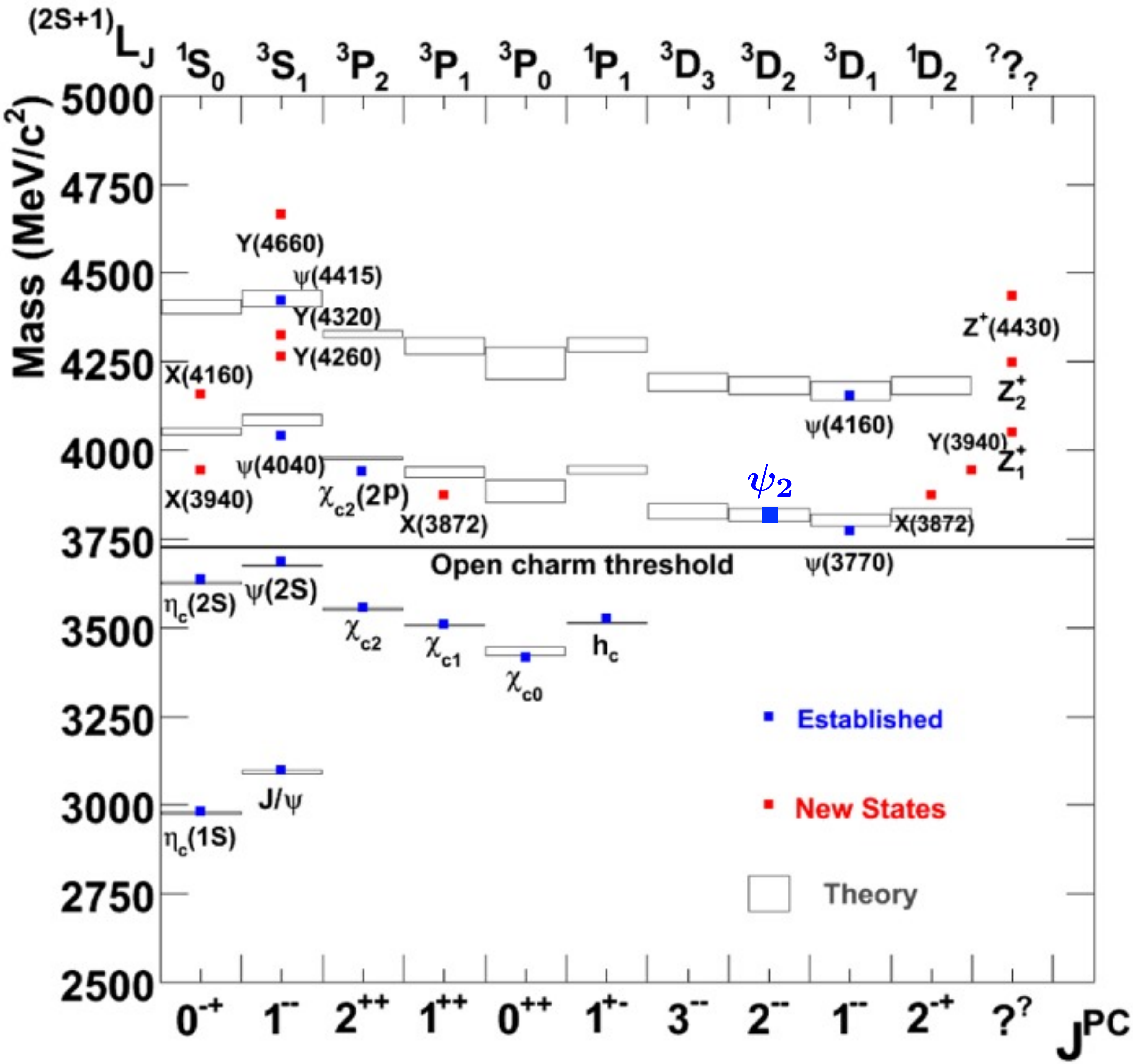
2003: the X(3872) is found in $B \to K\,(J/\psi\pi^+\pi^-)$ by Belle; confirmed by CDF, DØ, BaBar, LHCb, CMS

Steve Olsen snags a big one!



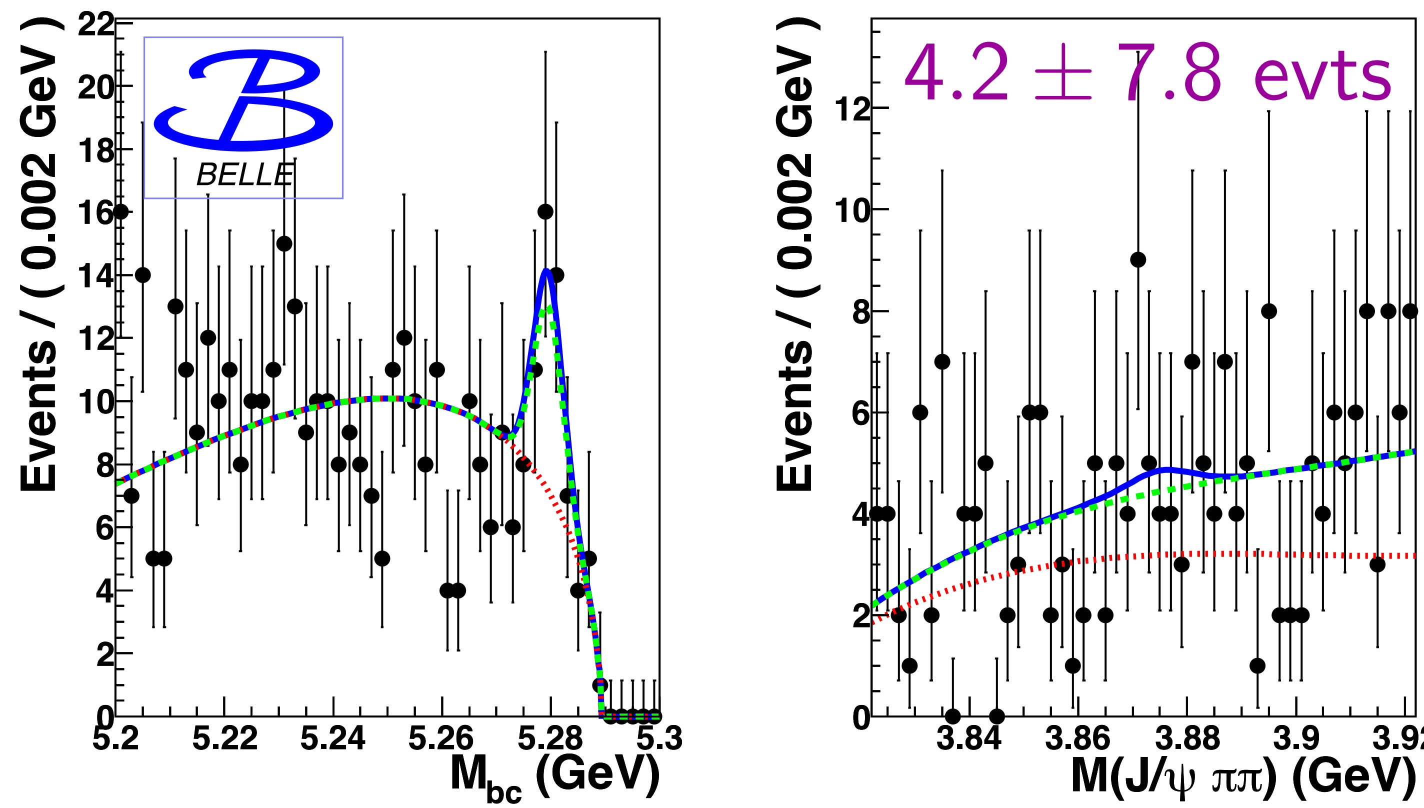
... and many more ☛

Exotic states ▪ *don't fit* charmonium predictions.



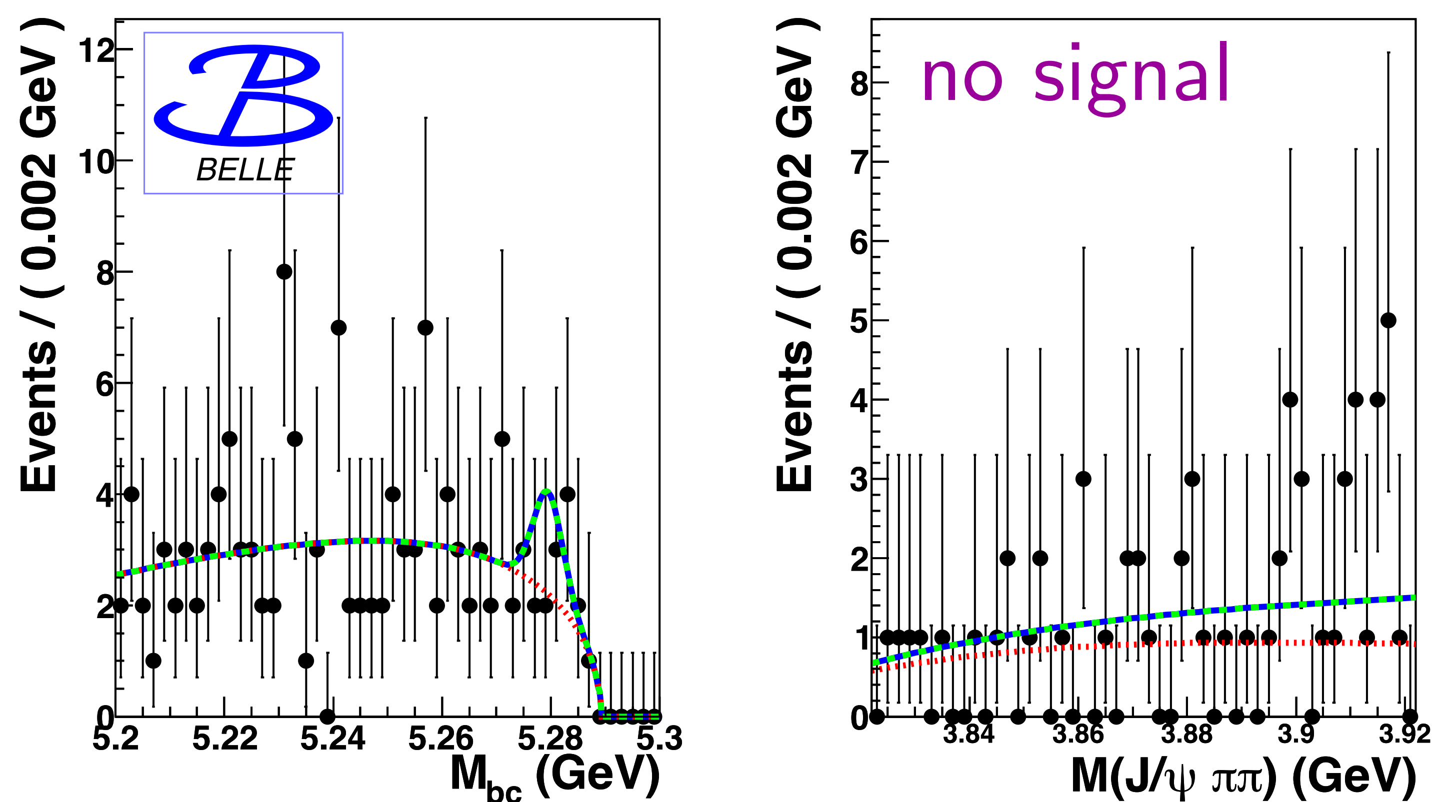
Isospin of $X(3872)$ is 0 since we don't see evidence for isovector partners $X^{\pm}$: favors $D^0\bar{D}^{*0}$ molecule over tetraquark model

$B^0 \to X^+K^-$ ▶



PRD 84, 052004 (2011)

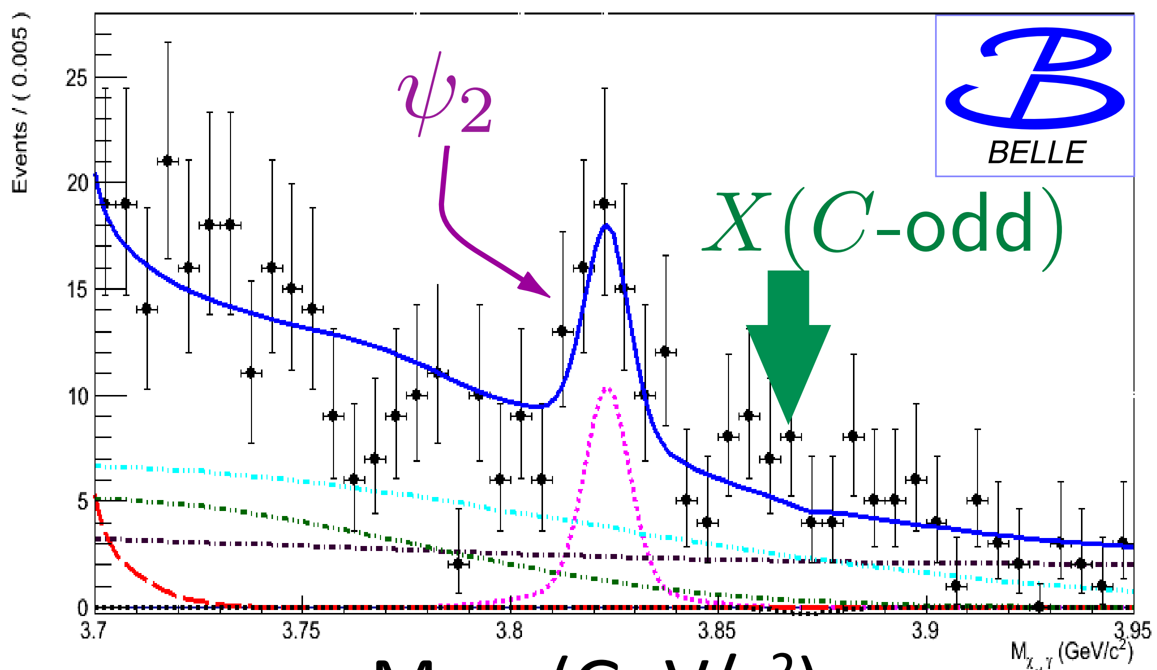
$B^+ \to X^+K^0$ ▶



Except the $X^{\pm}$ might be too broad to be seen! So ... look for the $C = -1$ neutral partner.

PRL 111, 032001 (2013)

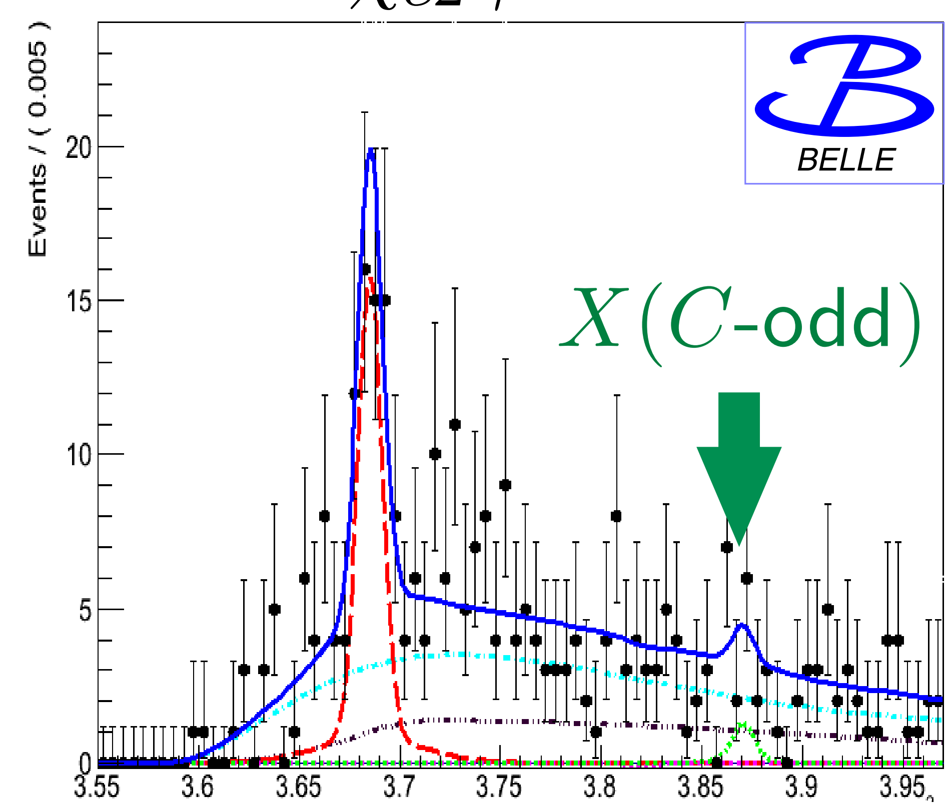
$B^+ \to \chi_{c1}\gamma K^+$



$M_{\chi c1\gamma}$ (GeV/c^2)

for $M_{\rm bc} > 5.27\,\text{GeV}/c^2$

$B^+ \to \chi_{c2}\gamma K^+$



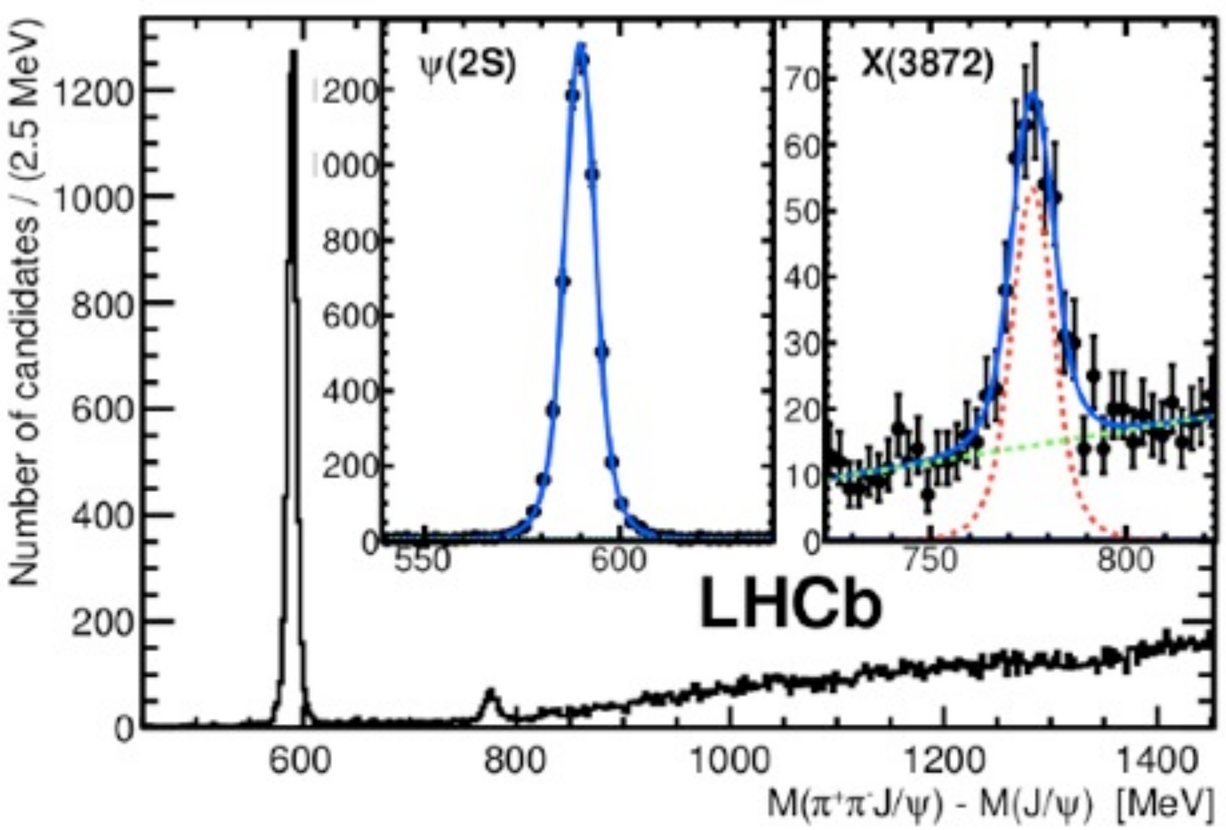
$M_{\chi c2\gamma}$ (GeV/c^2)

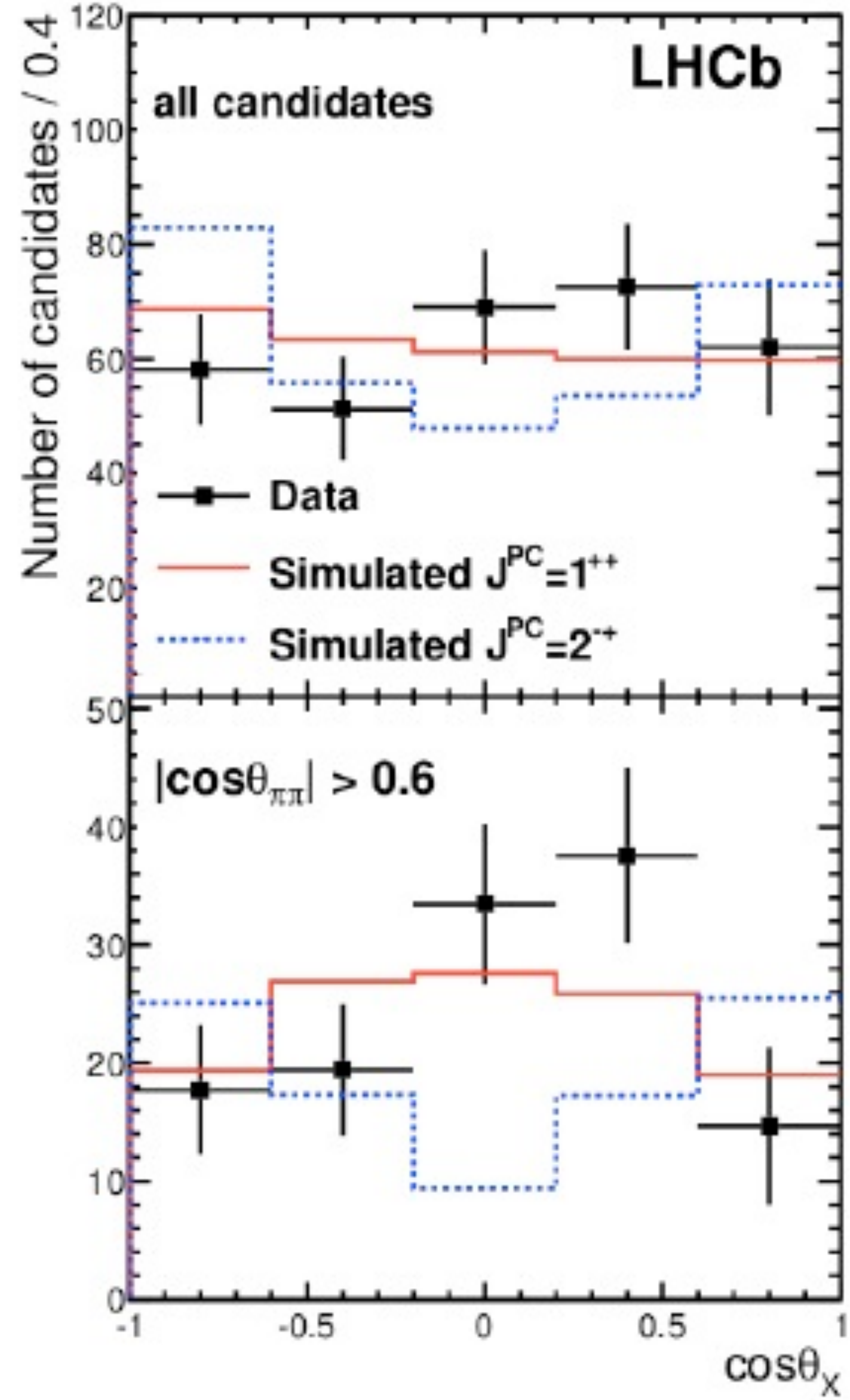
for $M_{\rm bc} > 5.27\,\text{GeV}/c^2$

No evidence for the $C = -1$ partner of the $X(3872)$ in $X \to \chi_{cJ}\gamma$ or $X \to J/\psi\,\eta$: disfavors tetraquark model.

LHCb data favor the 1^{++} over the 2^{-+} hypothesis for the X(3872) at 8.4σ and *closes the door for conventional charmonium*.

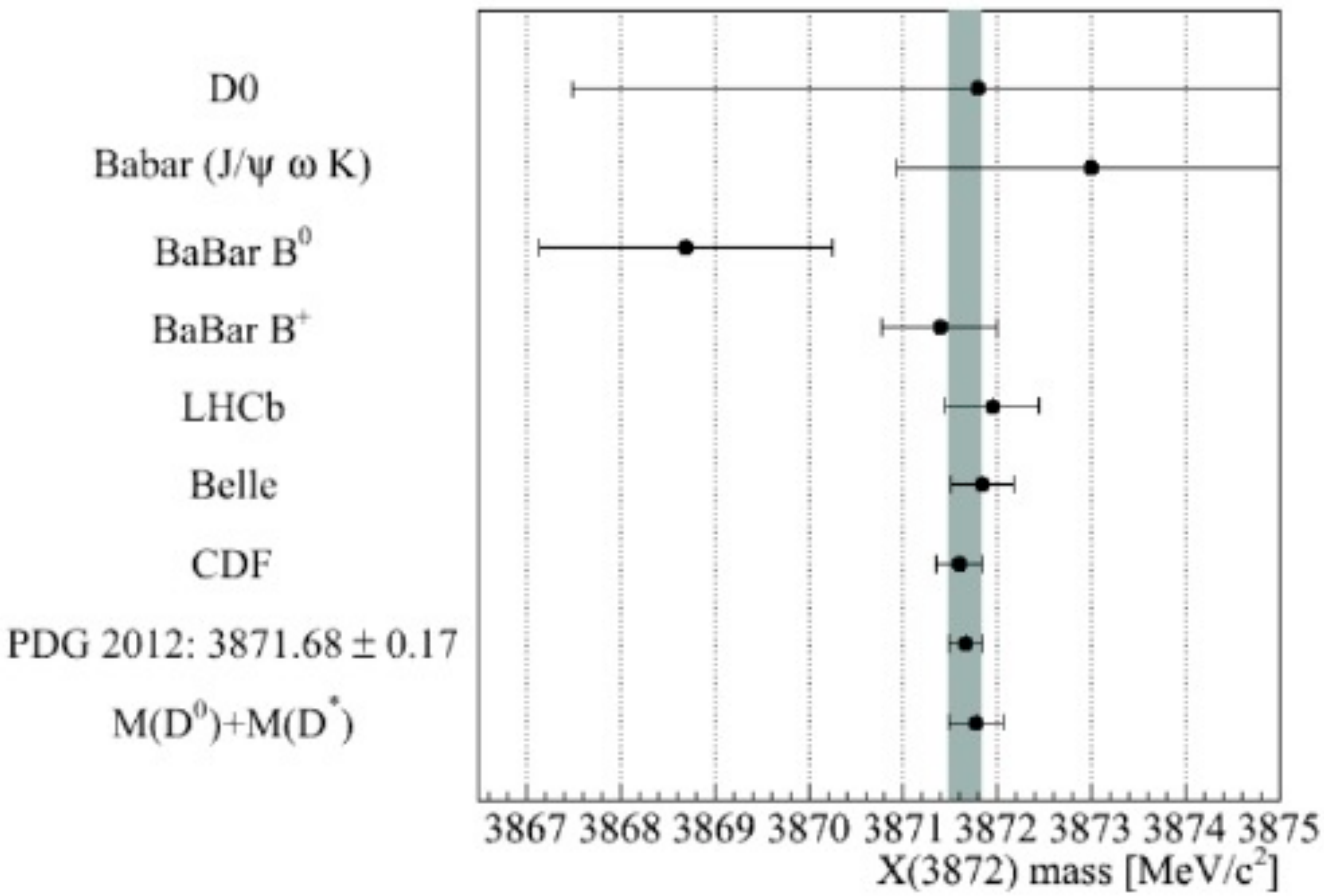
PRL 110, 222001 (2013)

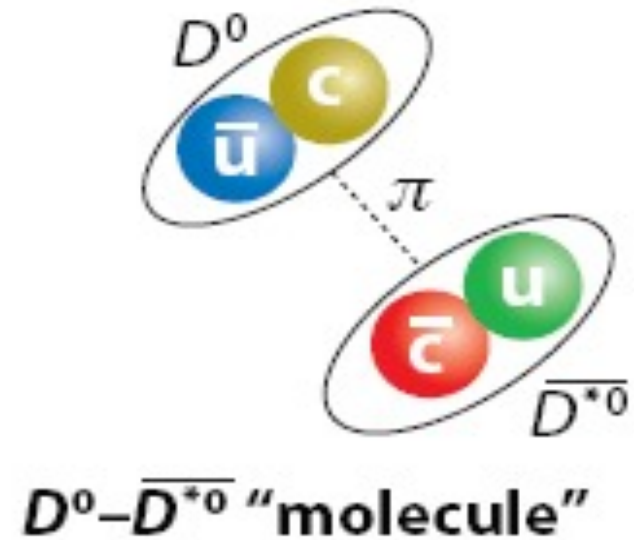




$X(3872)$ looks like a loosely bound $D^0\bar{D}^{*0}$ molecule

*predicted by N.A. Törnqvist: Z Phys C **61,** 525 (1994)*

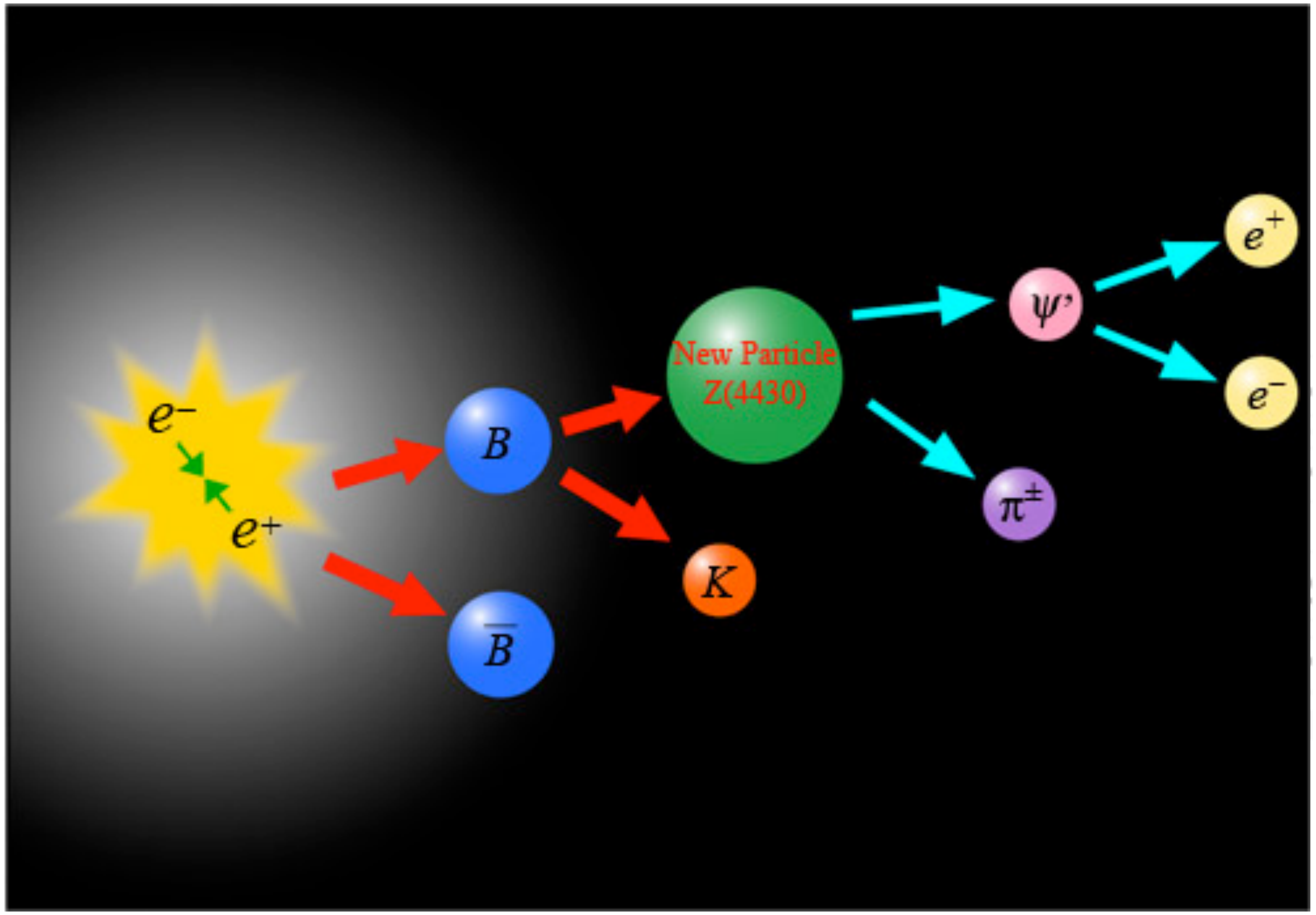




... but might have a small $c\bar{c}$ admixture.

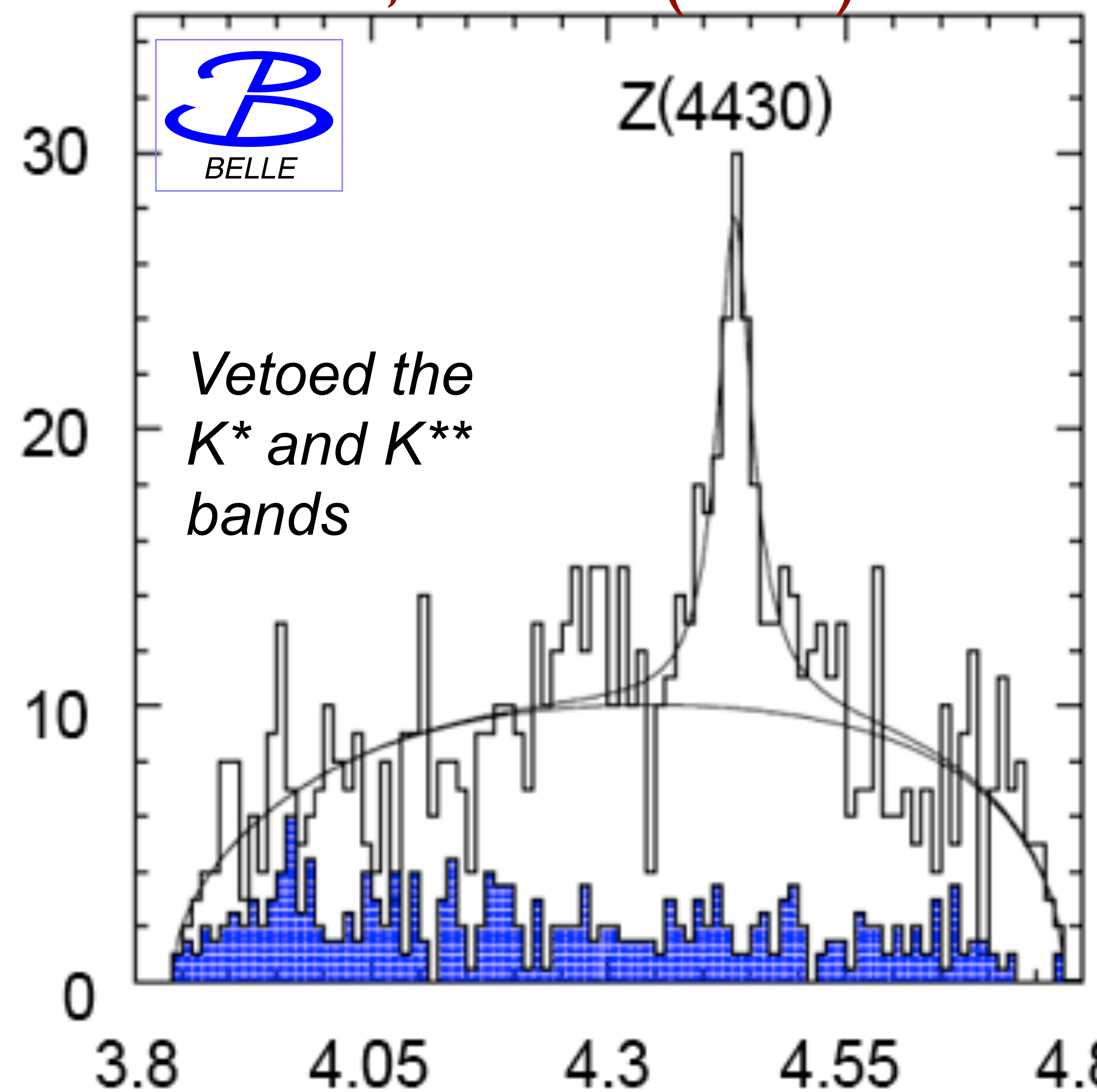
Tetraquark model is unlikely.

$Z(4430)$ is definitely not charmonium: it is charged.



Seen by Belle in $B \to K\,(\psi'\pi^\pm)$

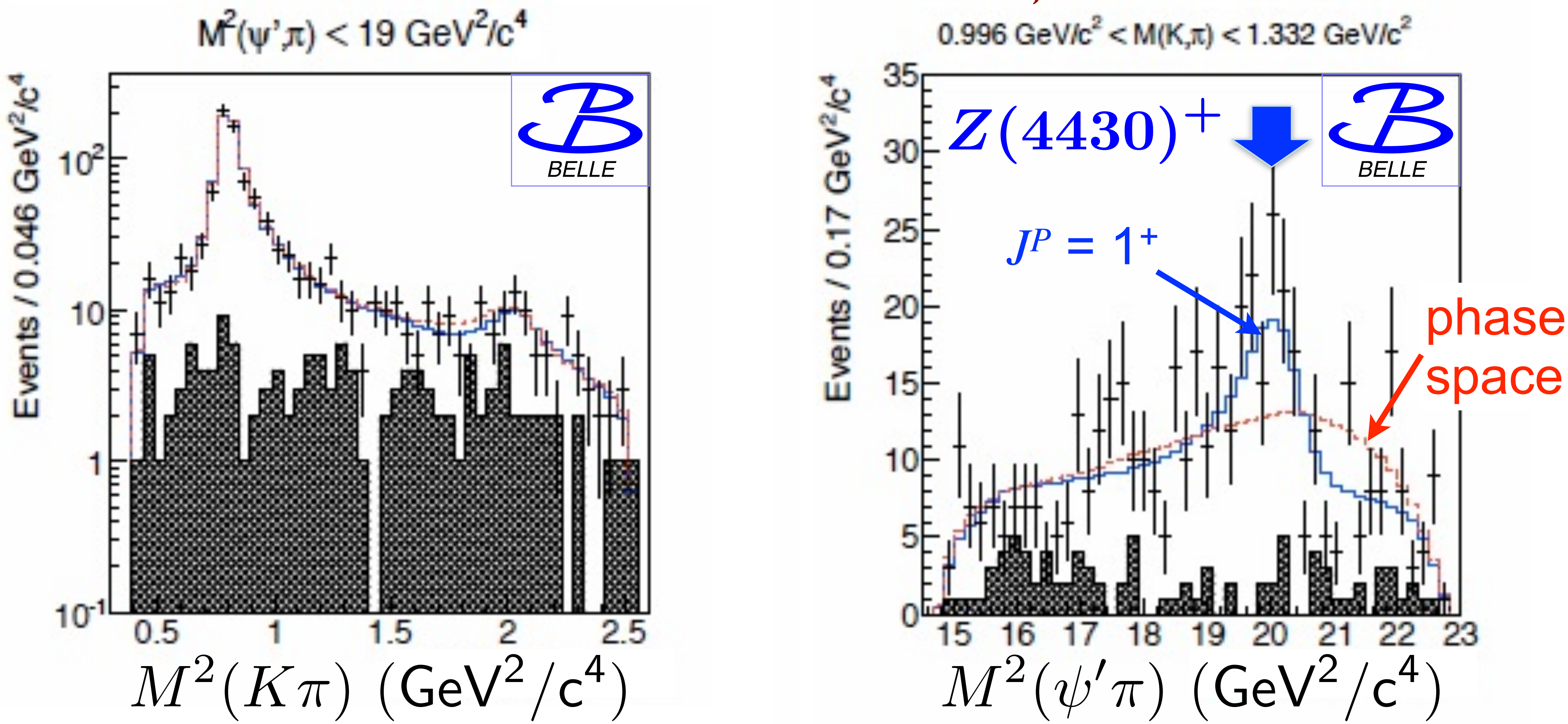
PRL 100, 142001 (2008)



Not seen by *BABAR* although their data are compatible with Belle's. "Artifact due to interference from K* resonances?"

Belle update: $Z(4430)^+$ still 5σ in full Dalitz analysis with interference and excited $K^{*(*)}$ resonances

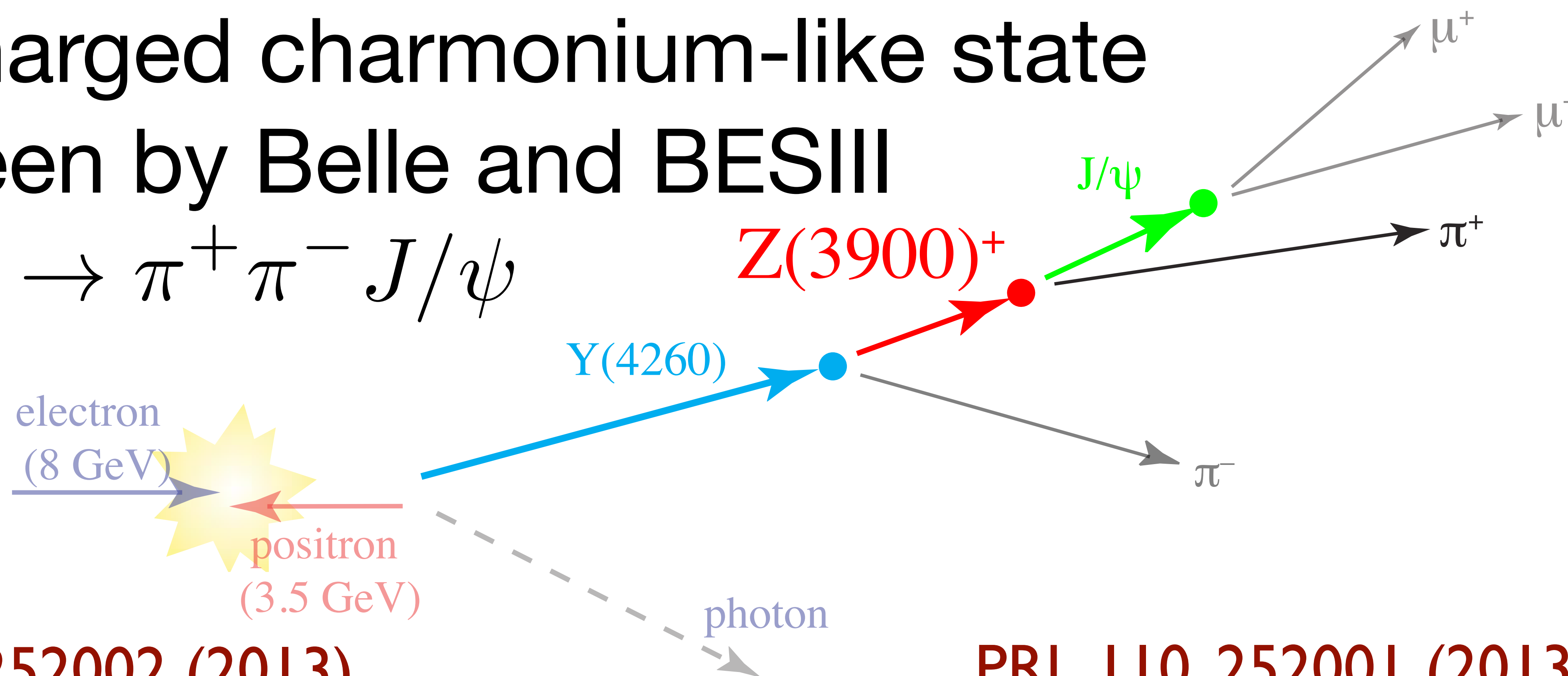
arXiv: 1306.4894, submitted to PRD



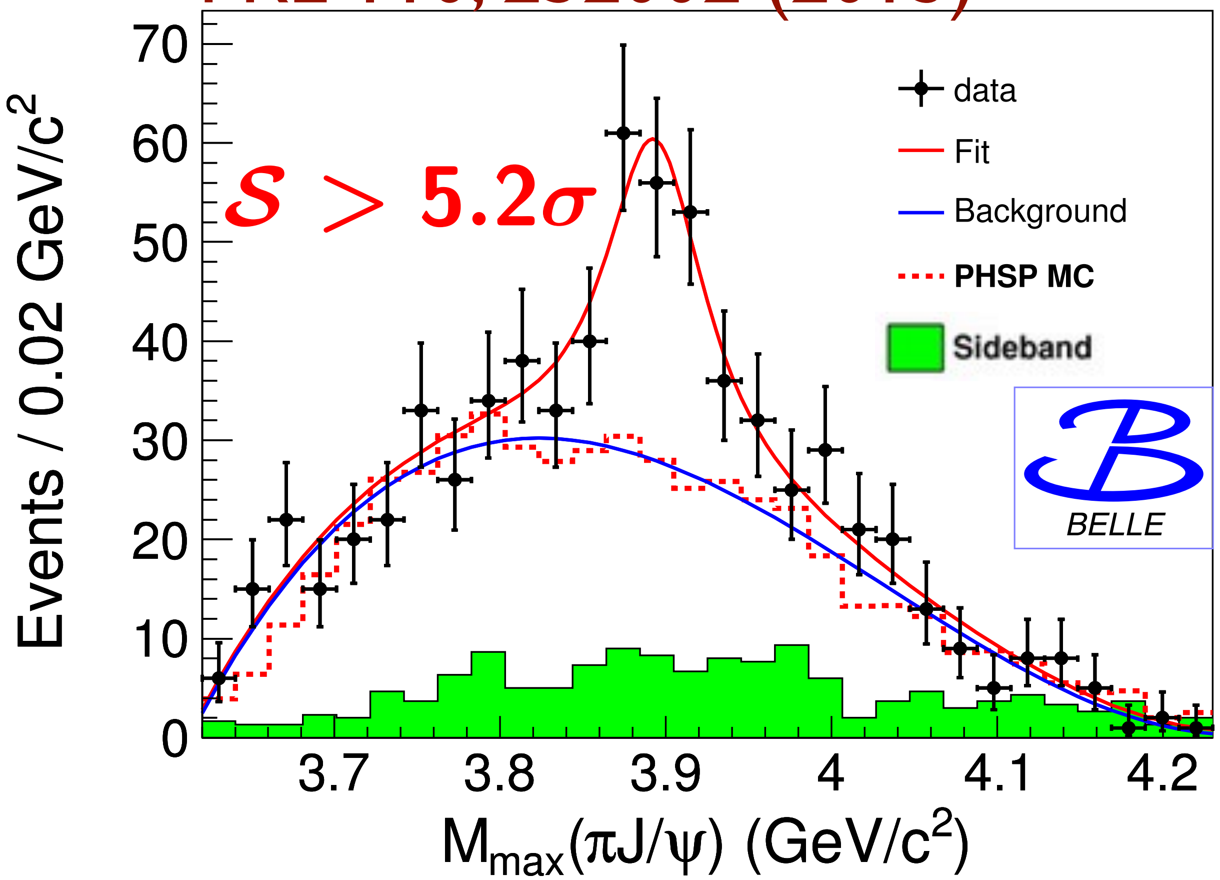
$J^P = 1^+$ is favoured over 0^- at the 2.9σ level. All other assignments are ruled out with over 4.3σ significance.

BaBar has been unable to confirm this state.
No reports from LHCb, CDF, etc… yet.

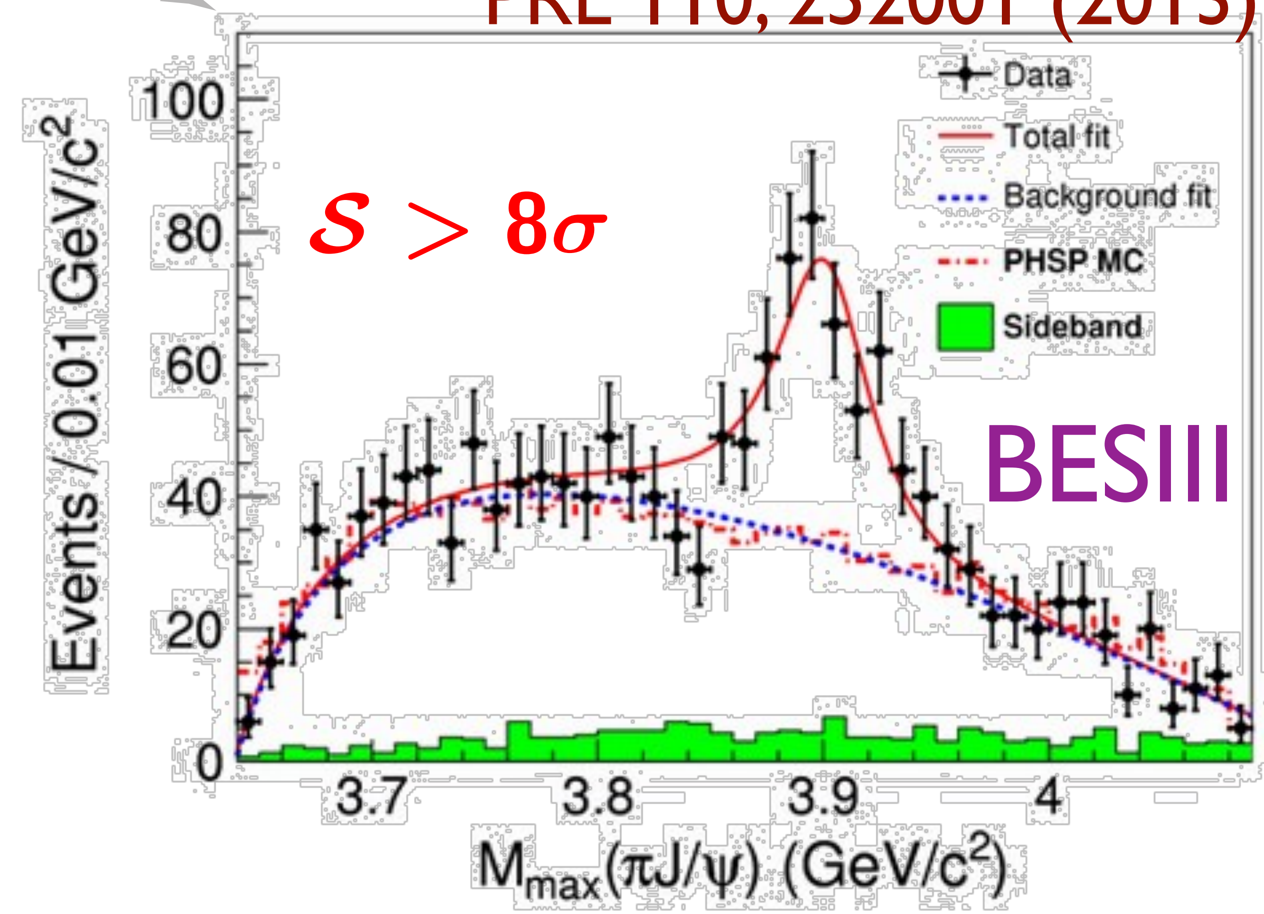
Another charged charmonium-like state $Z(3900)^+$ seen by Belle and BESIII in $Y(4260) \to \pi^+\pi^- J/\psi$



PRL 110, 252002 (2013)



PRL 110, 252001 (2013)

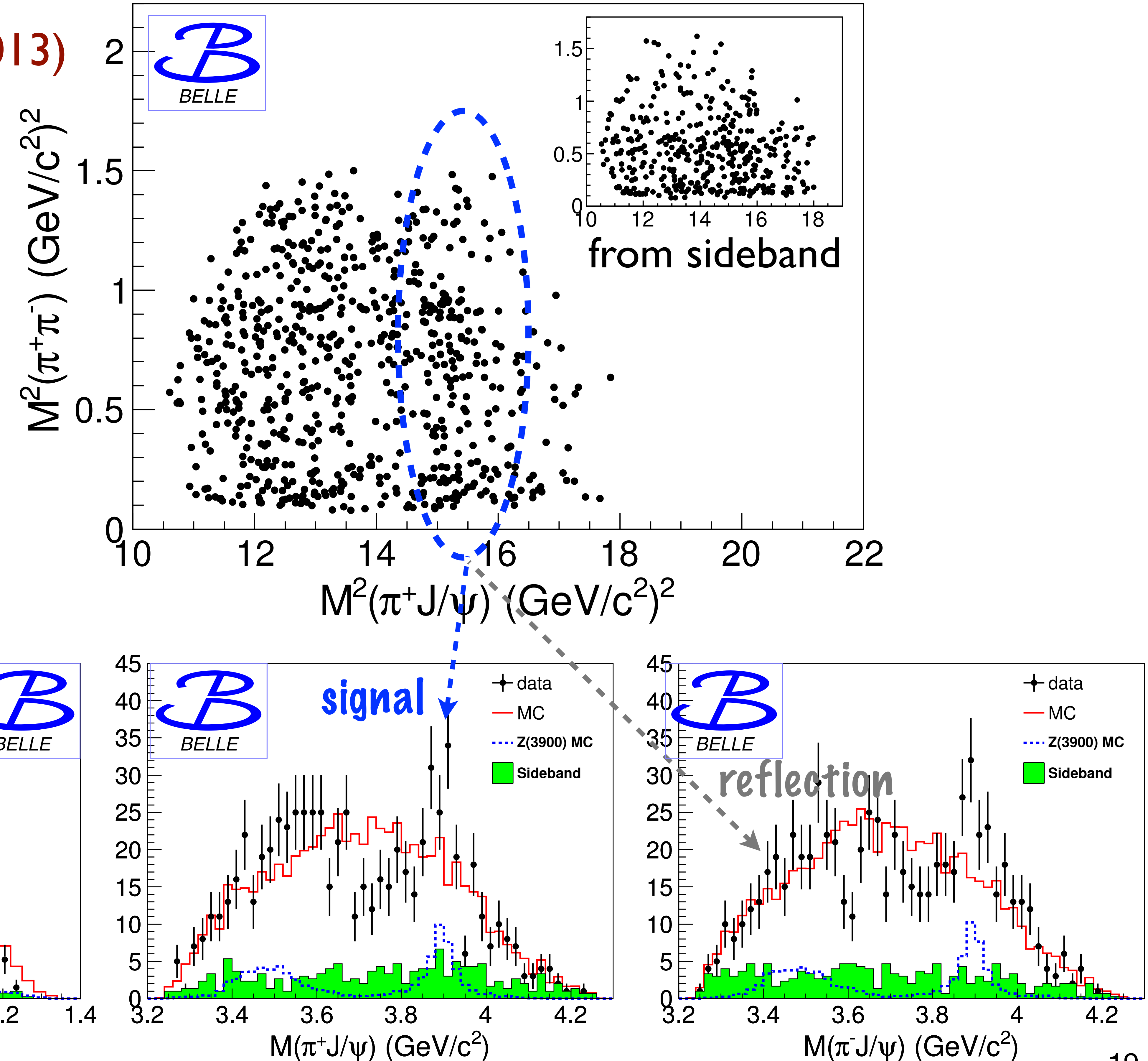


$$M = (3894.5 \pm 6.6 \pm 4.5)\ \text{MeV}$$
$$\Gamma = (63 \pm 24 \pm 26)\ \text{MeV}$$

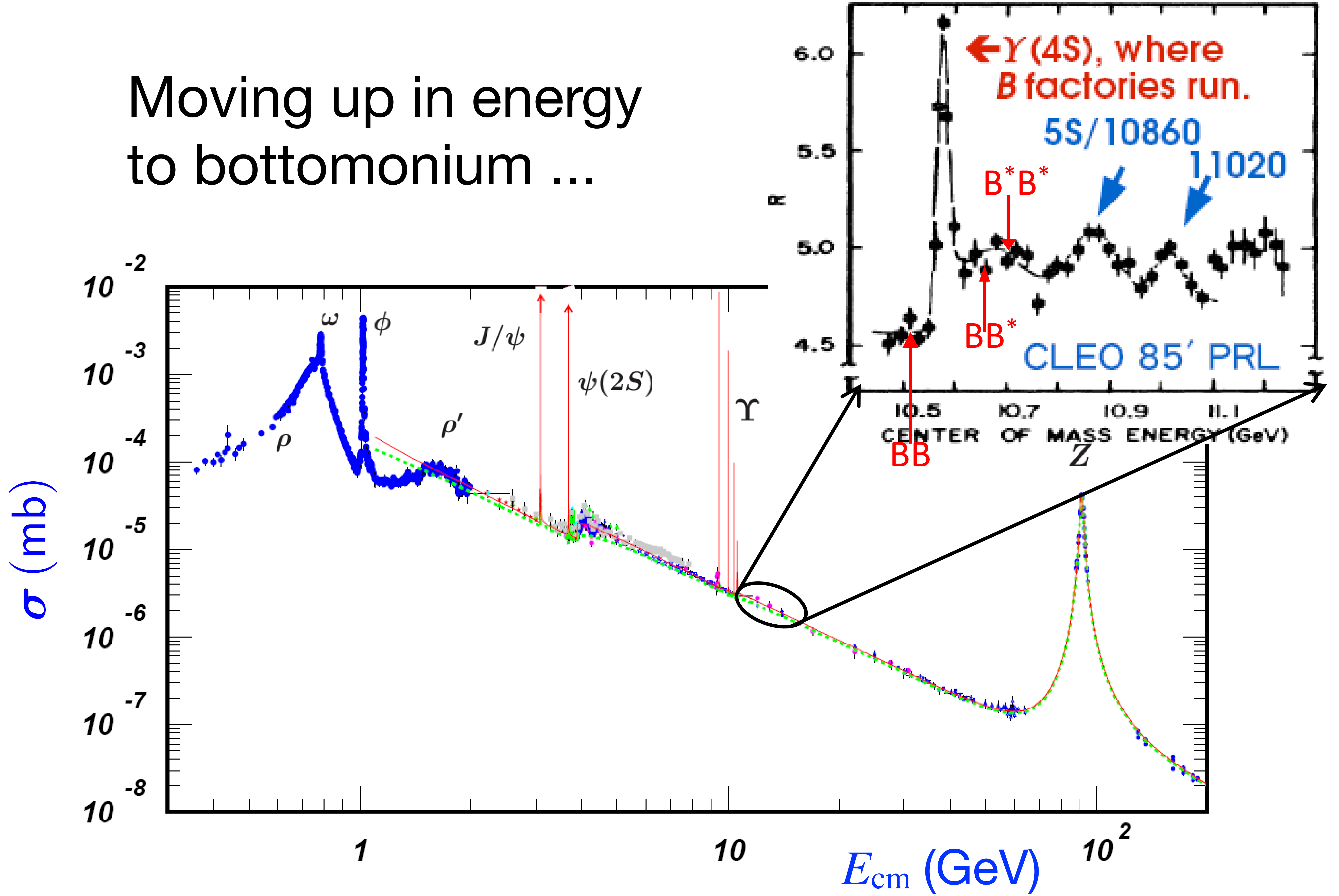
$$M = (3899.0 \pm 3.6 \pm 4.9)\ \text{MeV}$$
$$\Gamma = (46 \pm 10 \pm 20)\ \text{MeV}$$

Dalitz plot and projections for $Z(3900)^+$

PRL 110, 252002 (2013)



Moving up in energy to bottomonium ...



$\Upsilon(5S)$ has anomalously high rates to $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

PRL 100, 112001 (2008)

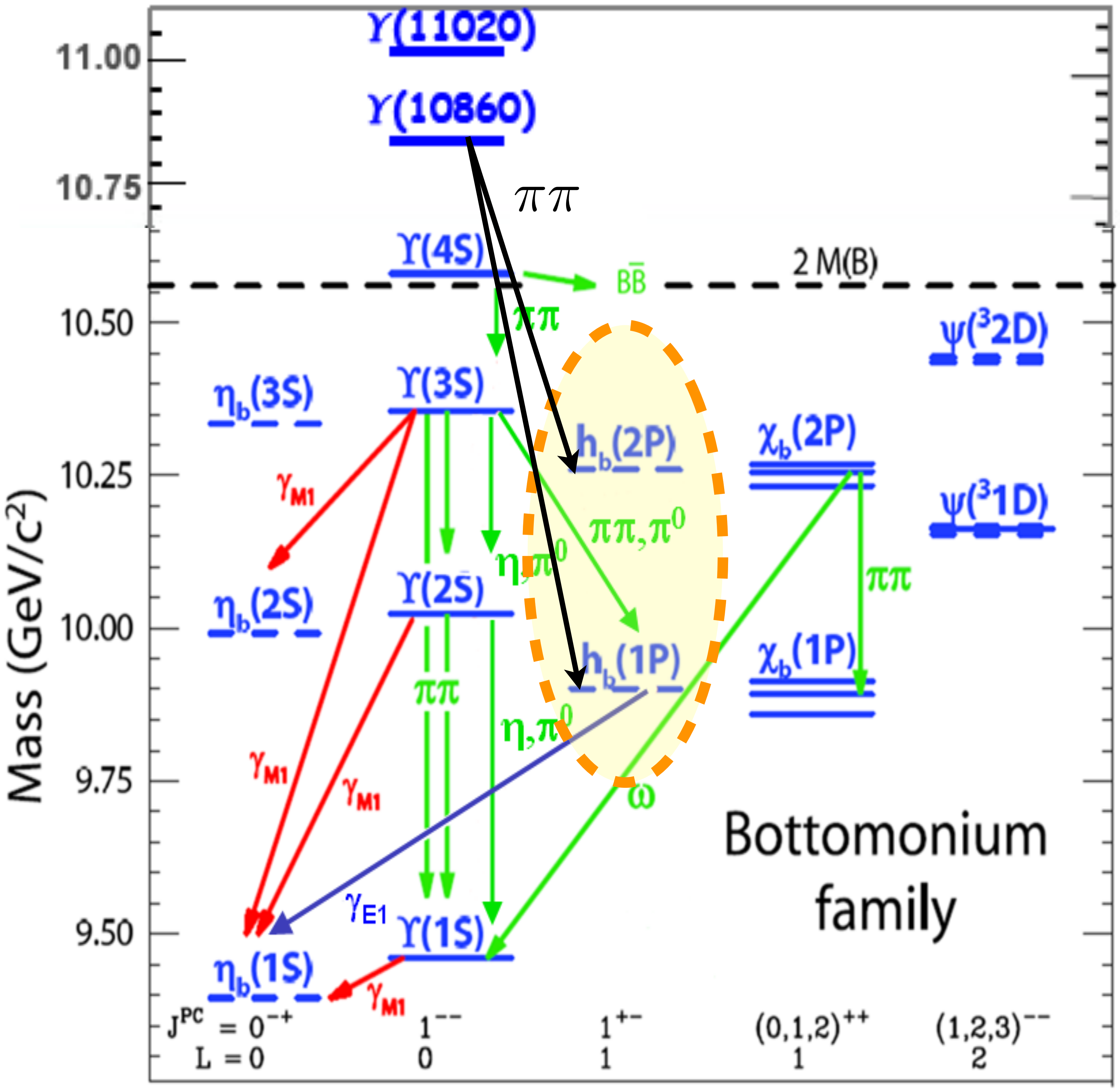
BELLE

	$\Gamma(\mathrm{MeV})$
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

≈2 orders of magnitude greater ?!?

Perhaps the "$\Upsilon(5S)$" is an admixture of $b\bar{b}$ and the Y_b ... the counterpart of $Y(4260)$ in charmonium. Anyway, let's do something useful with this "$\Upsilon(5S)$".

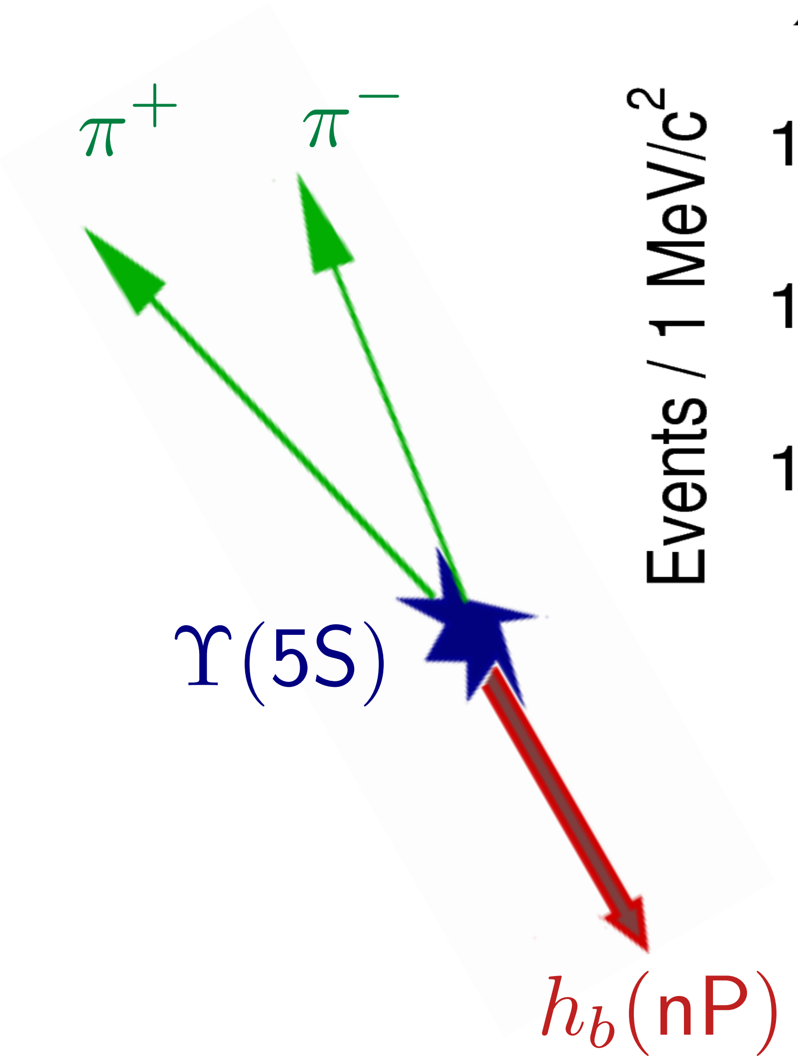
Look for h_b and $h_b(2P)$ in $\Upsilon(5S) \to \pi^+\pi^-$ (anything)

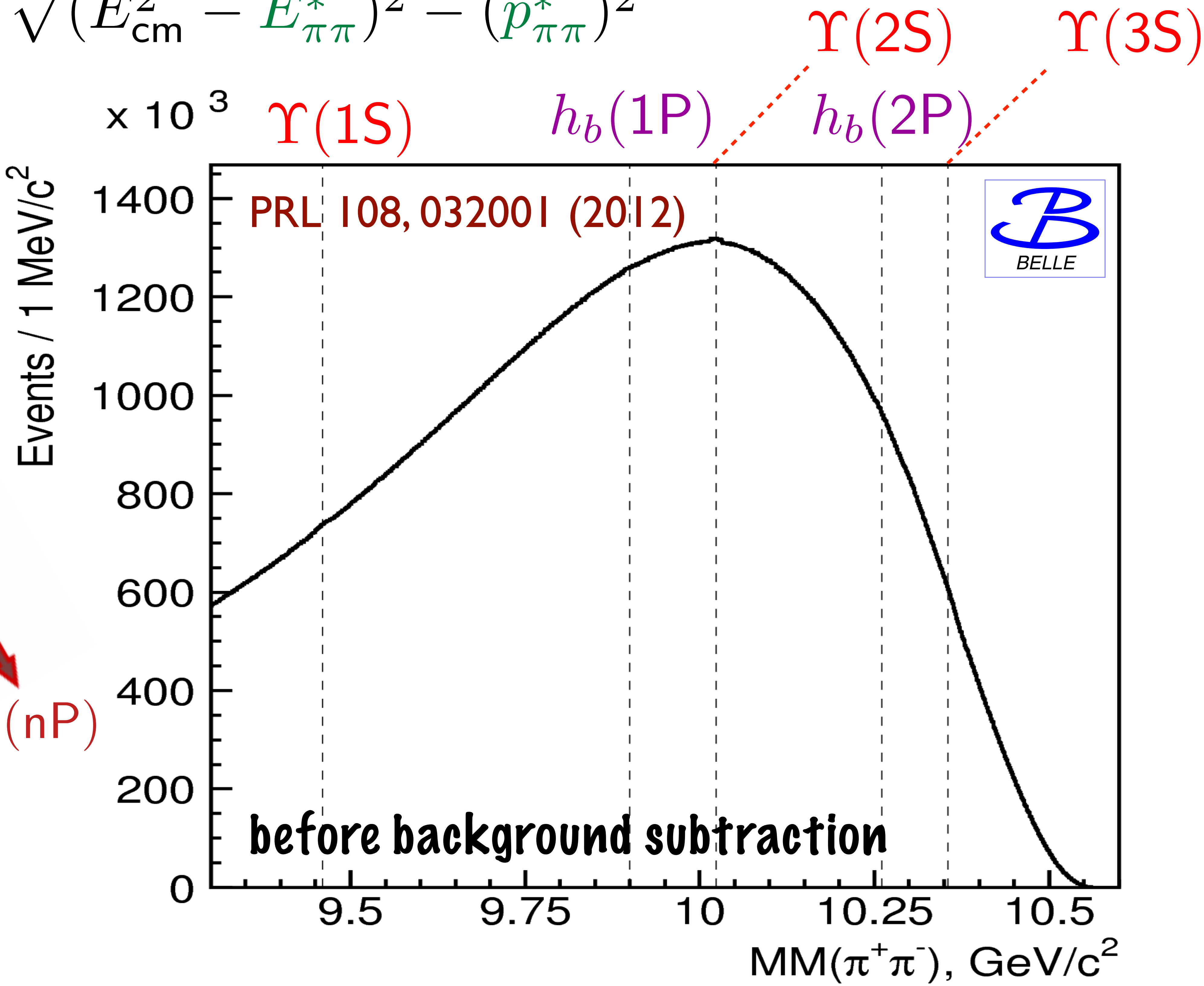


Use missing-mass technique to find h_b and $h_b(2P)$

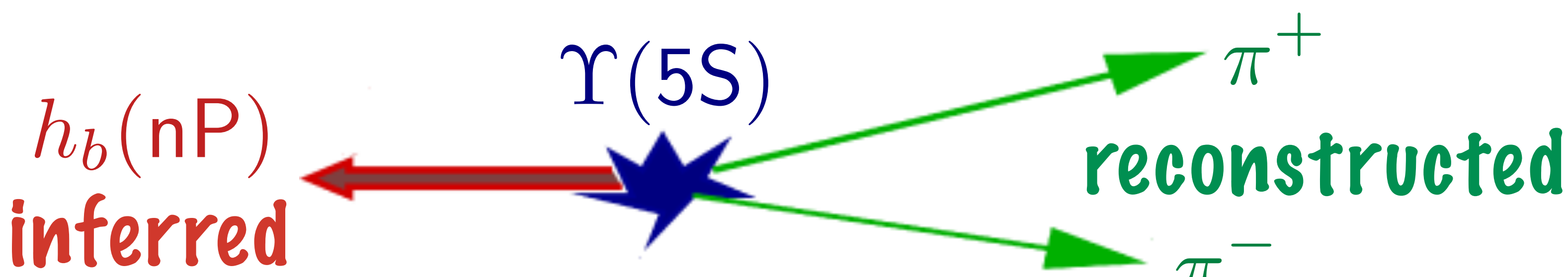
since there aren't any useful h_b final states

$$MM(\pi\pi) = \sqrt{(E_{cm}^2 - E_{\pi\pi}^*)^2 - (p_{\pi\pi}^*)^2}$$

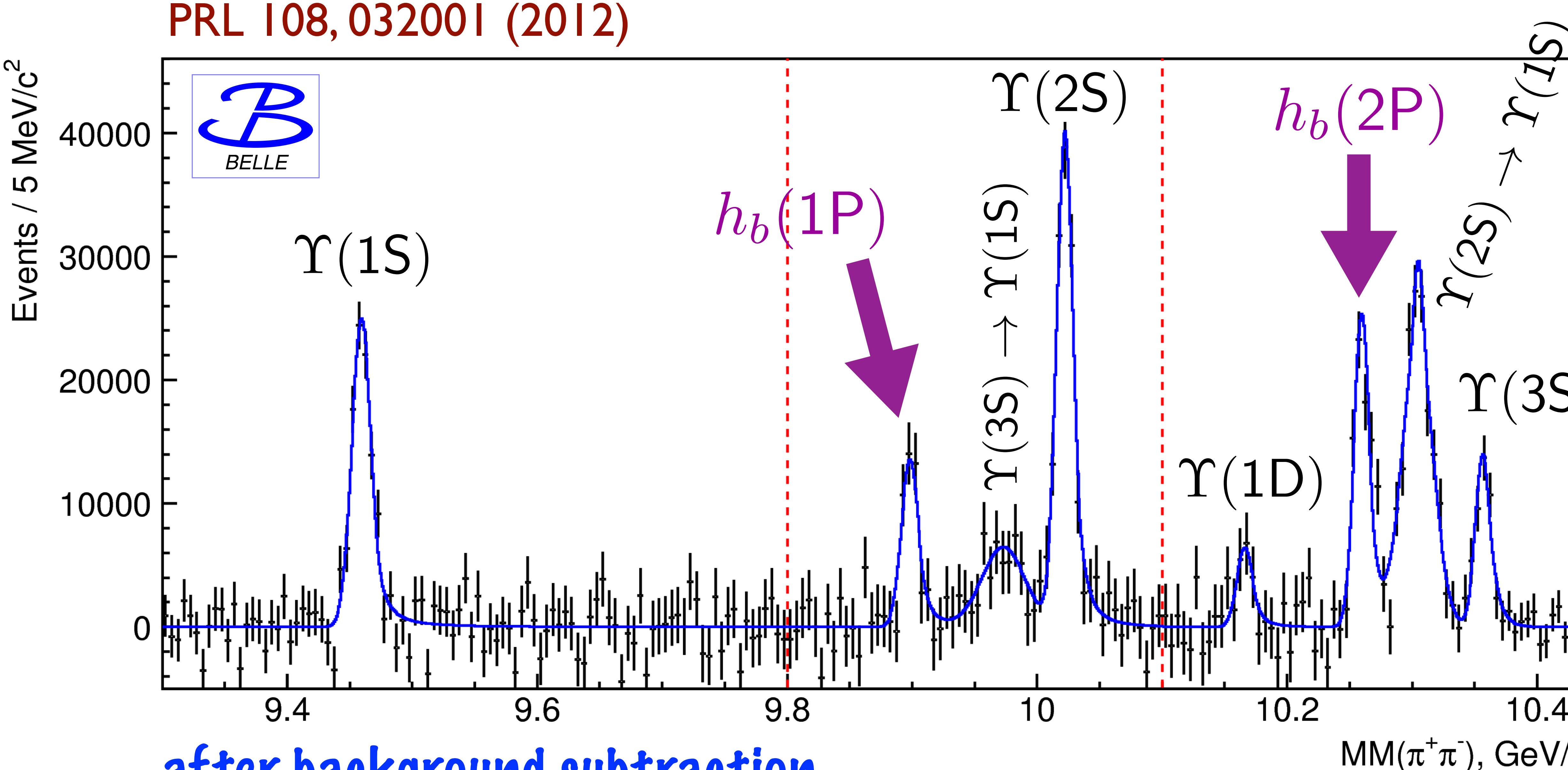




Use missing-mass technique to find h_b and $h_b(2P)$

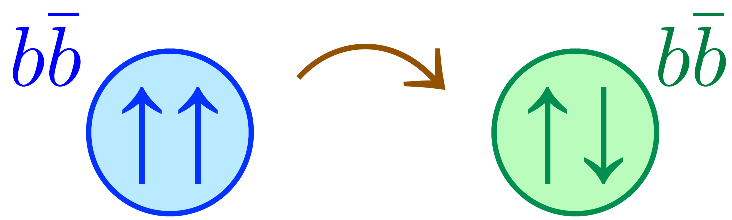


PRL 108, 032001 (2012)



after background subtraction

The width of $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ is unusually large, given the spin flip of a b quark



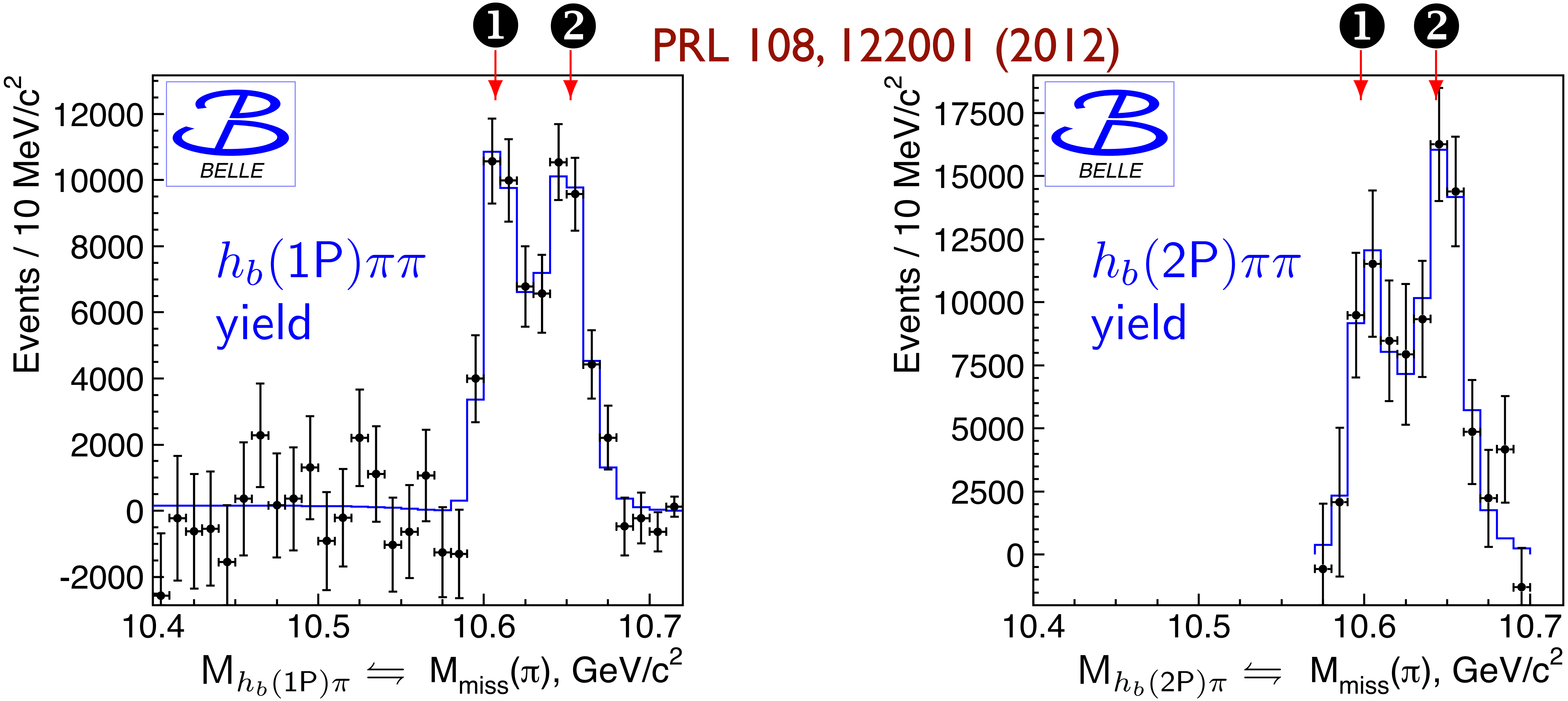
$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08 \pm {}^{0.07}_{0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08 \pm {}^{0.22}_{0.17} & \text{for } h_b(2P) \end{cases}$$

It should be suppressed as $\sim (\Lambda_{QCD}/m_b)^2$

$\Rightarrow$ something unusual here ...

$\Upsilon(5S) \to h_b(\mathrm{nP})\pi^+\pi^-$ proceeds via 2 resonances!

PRL 108, 122001 (2012)



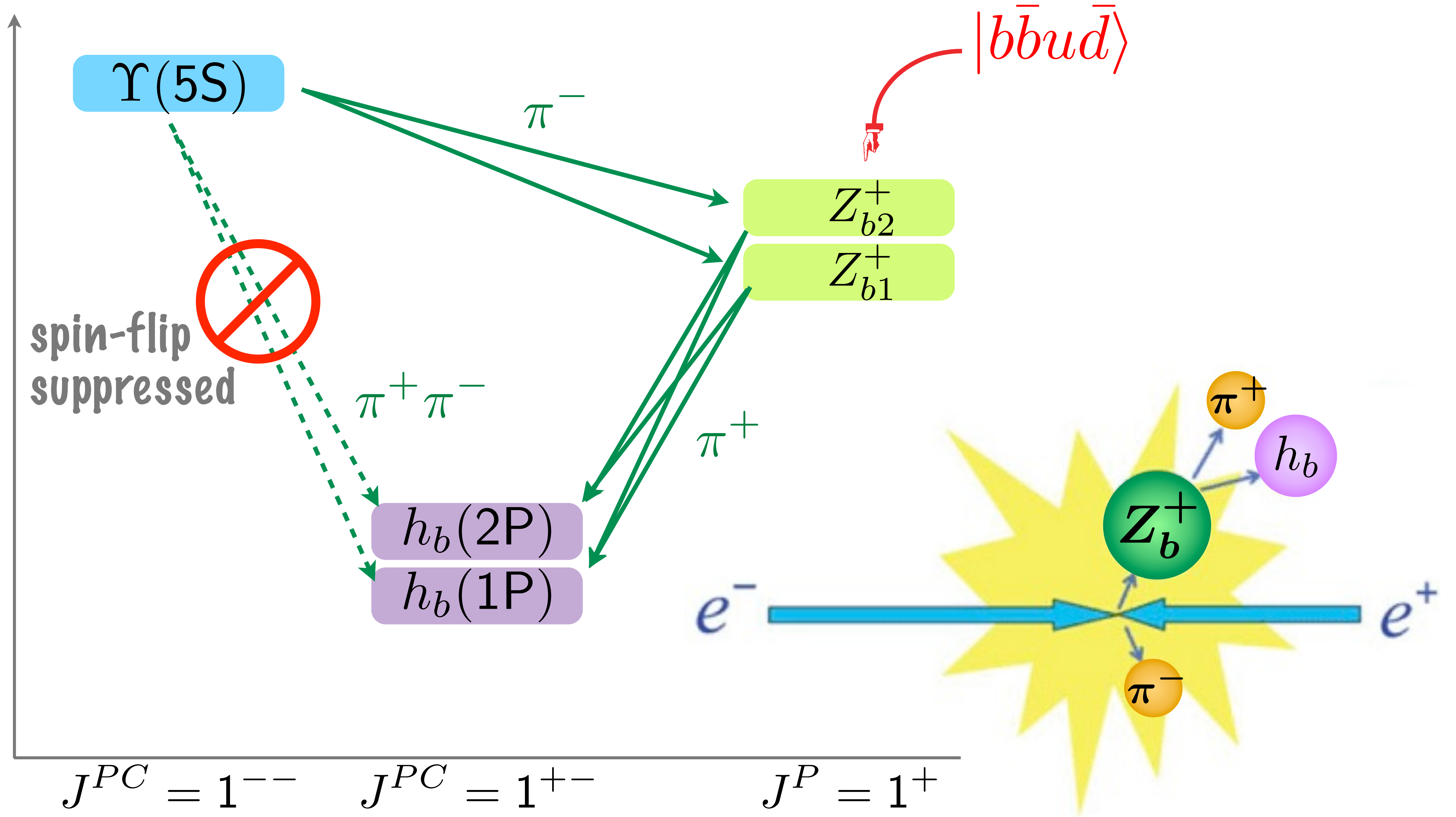
$$M_1 = 10605 \pm 2 \pm^{3}_{1}\ \mathrm{MeV} \quad \Leftrightarrow \quad M_1 = 10599 \pm^{6}_{3} \pm^{5}_{4}\ \mathrm{MeV}$$

$$\Gamma_1 = 11.4 \pm^{4.5}_{3.9} \pm^{2.1}_{1.2}\ \mathrm{MeV} \quad \quad \Gamma_1 = 13 \pm^{10}_{8} \pm^{9}_{7}\ \mathrm{MeV}$$

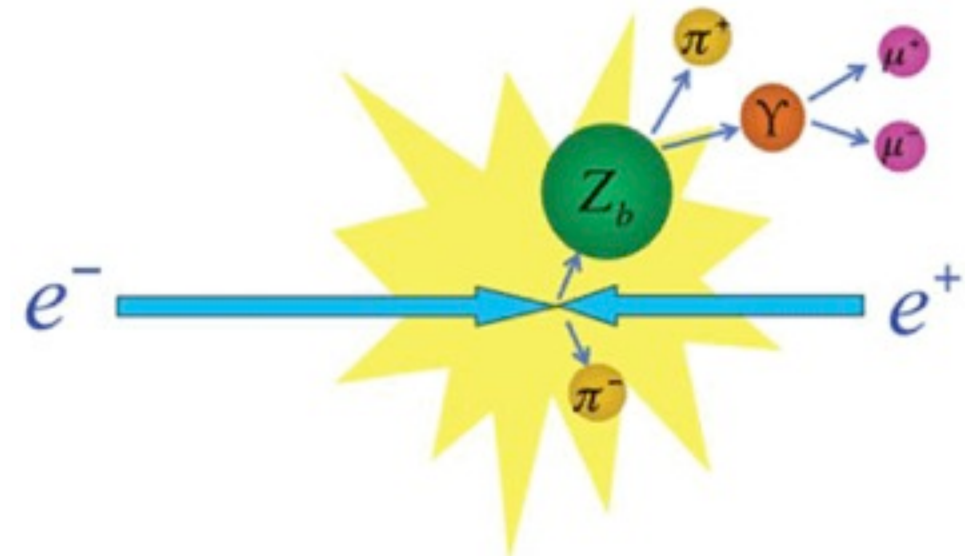
$$M_2 = 10654 \pm 3 \pm^{1}_{2}\ \mathrm{MeV} \quad \Leftrightarrow \quad M_2 = 10651 \pm^{2}_{3} \pm^{3}_{2}\ \mathrm{MeV}$$

$$\Gamma_2 = 20.9 \pm^{5.4}_{4.7} \pm^{2.1}_{5.7}\ \mathrm{MeV} \quad \quad \Gamma_2 = 19 \pm 7 \pm^{11}_{7}\ \mathrm{MeV}$$

$\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ proceeds via one of two intermediate exotic states, Z_{b1}^+ and Z_{b2}^+

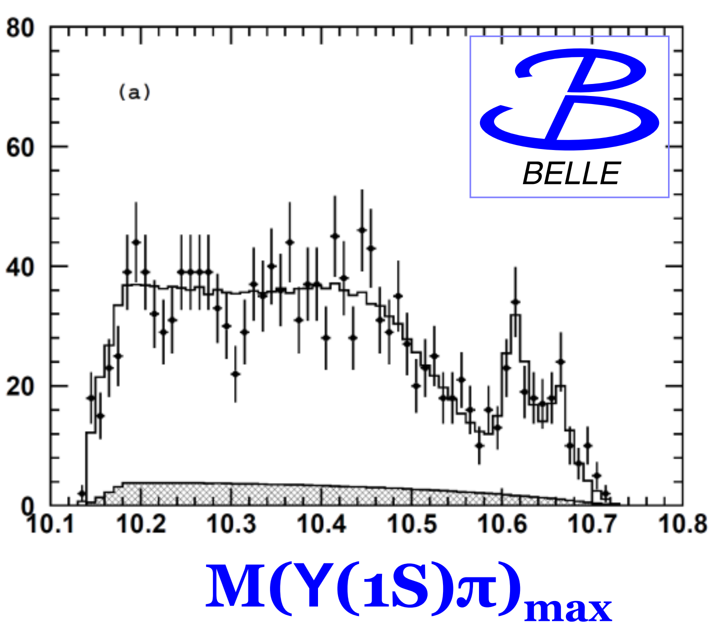


The same intermediate states appear in $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

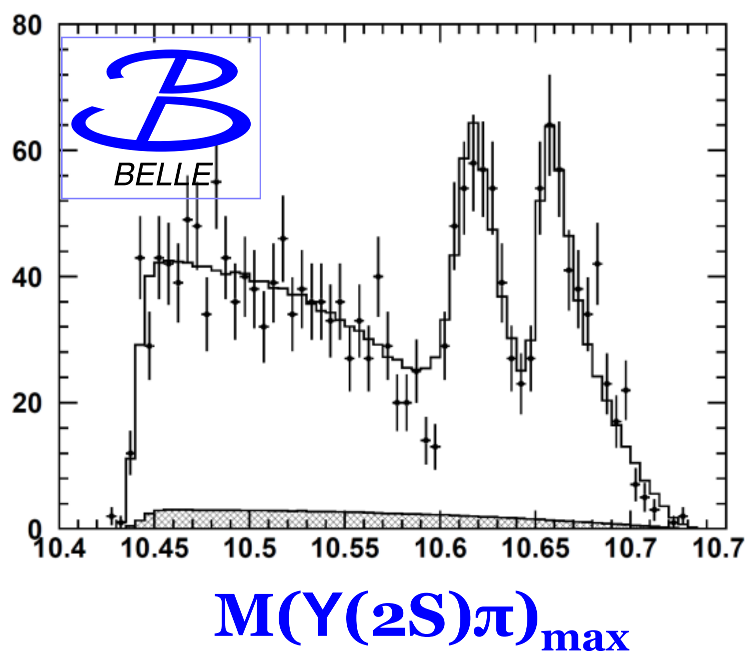


PRL 108, 122001 (2012)

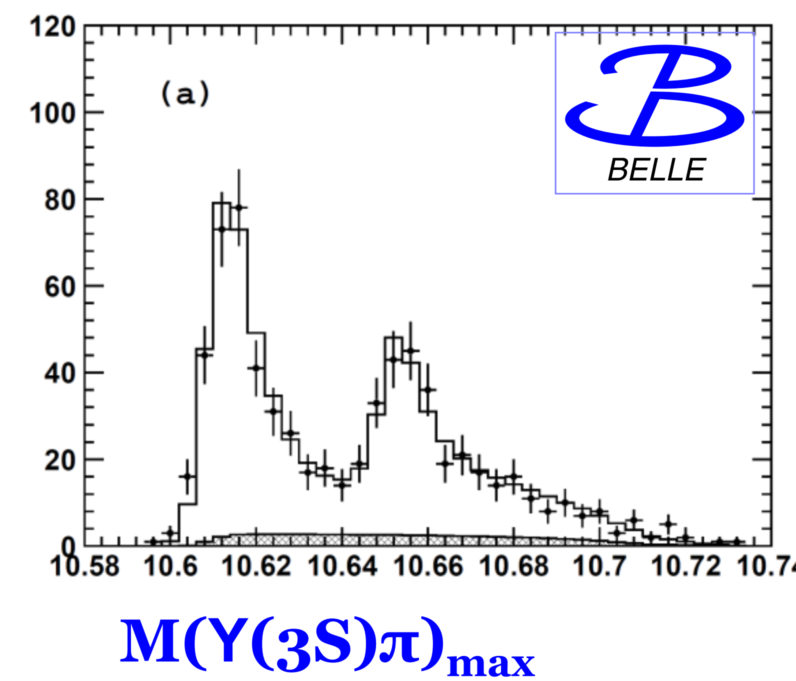
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$



$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$

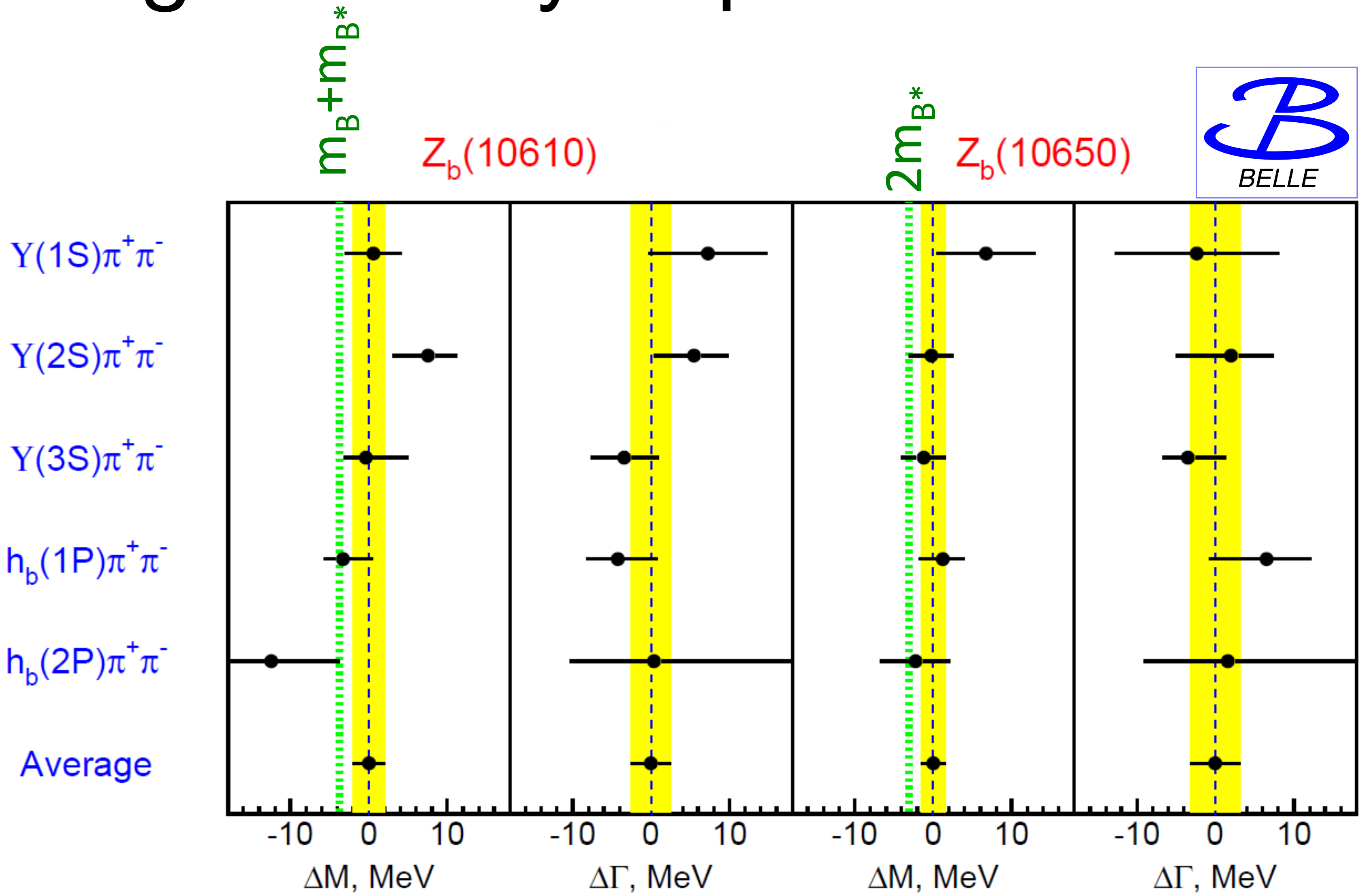


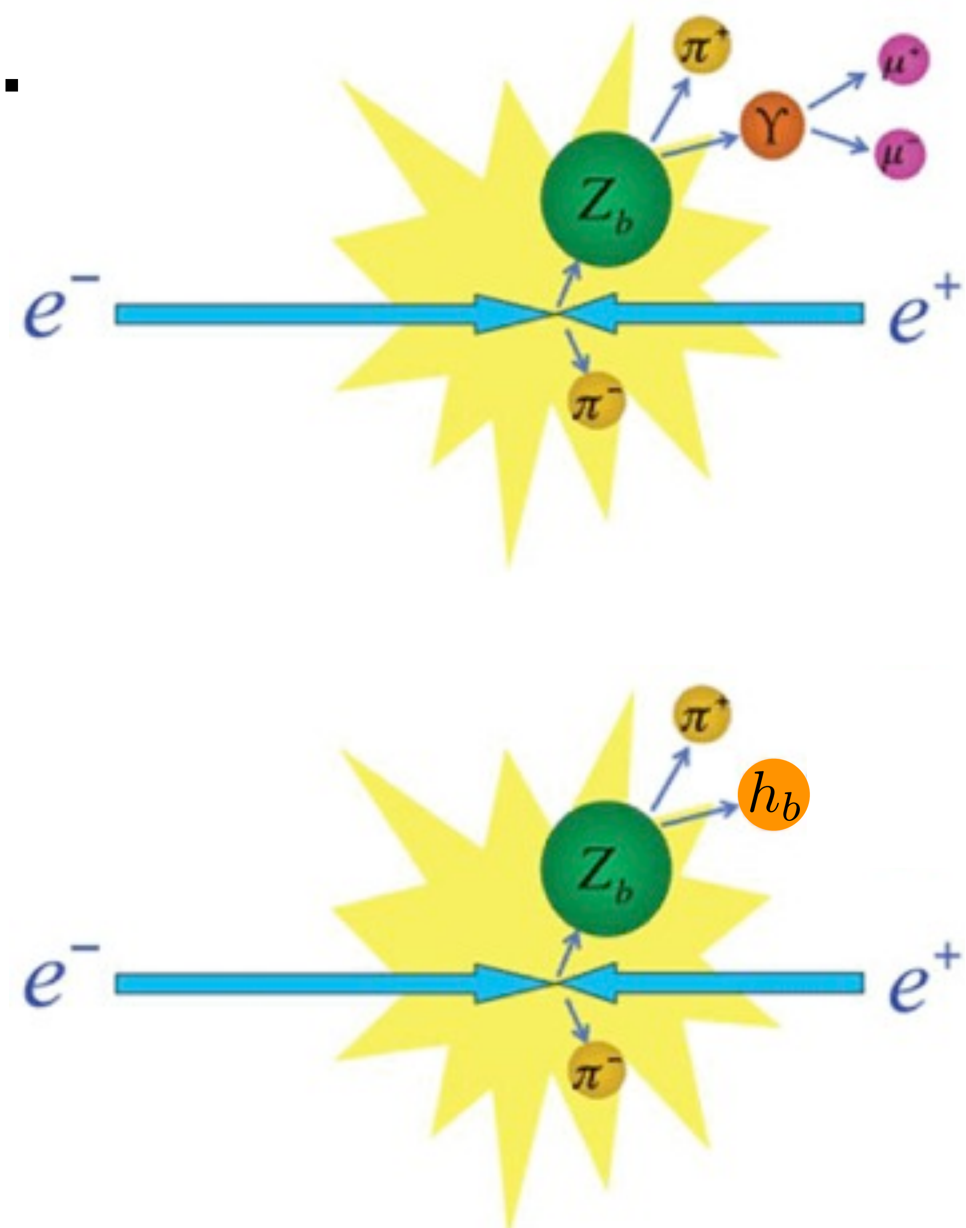
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$



	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
Z_{b1}	M=10611±4±3 MeV Γ=22.3±7.7±4.0 MeV	M=10609±2±3 MeV Γ=24.2±3.1±3.0 MeV	M=10608±2±3 MeV Γ=17.6±3.0±3.0 MeV
Z_{b2}	M=10657±6±3 MeV Γ=16.3±9.8±6.0 MeV	M=10651±2±3 MeV Γ=13.3±3.3±4.0 MeV	M=10652±1±2 MeV Γ=8.4±2.0±2.0 MeV

Belle obtains consistent mass and width of $Z_b^{\pm}$ in all 5 measurements.
Angular analysis prefers $J^P = 1^+$.





$Z_b(10610)$

M=10607.2±2.0 MeV

Γ=18.4±2.4 MeV

$Z_b(10650)$

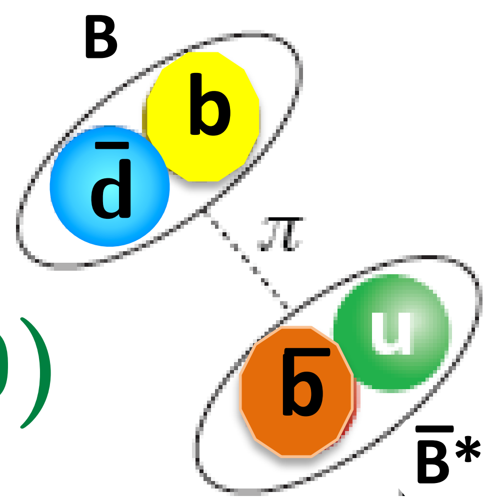
M=10652.2±1.5 MeV

Γ=11.5±2.2 MeV

PRL 108, 122001 (2012)

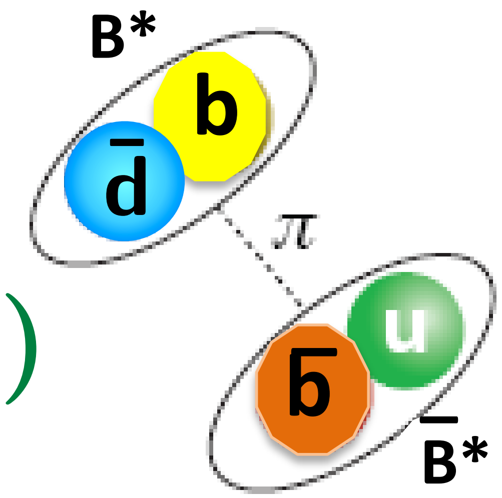
Perhaps these are $B\,\bar{B}^*$ and $B^*\,\bar{B}^*$ molecules

$Z_b^+(10610)$



B-$\bar{B}$* “molecule”

$Z_b^+(10650)$



B*-$\bar{B}$* “molecule”

$$M_{Z_b(10610)} - (M_B + M_{B^*}) = +2.7 \pm 1.8\,\text{MeV}$$

$$M_{Z_b(10650)} - 2M_{B^*} = +2.0 \pm 1.8\,\text{MeV}$$

$Z_b^\pm$ was discovered in $h_b \pi^\pm$ and then $\Upsilon \pi^\pm$, but it prefers to decay to $B^{(*)} \bar{B}^*$

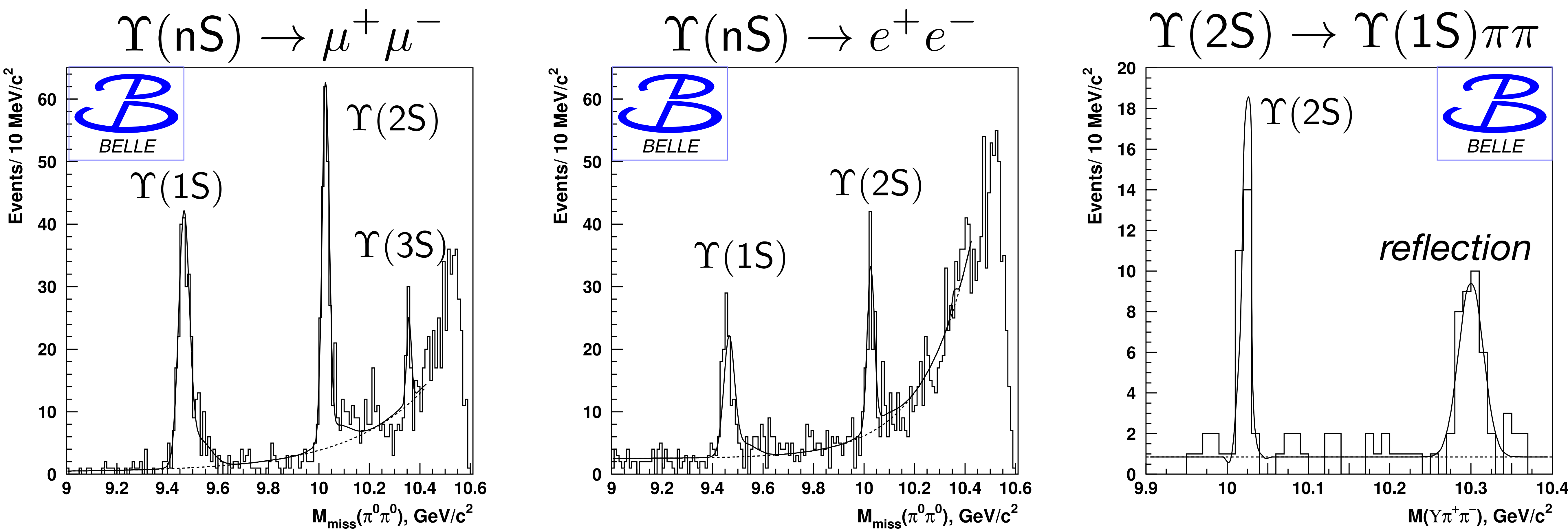
Assuming Z_b decays to $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ only:

Channel	$\mathcal{B}$ of $Z_b(10610)$, %	$\mathcal{B}$ of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

BELLE arXiv: 1209.6450

The neutral partner, $Z_b^0(10610)$, is also seen by Belle in $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$

arXiv: 1308.2646, submitted to PRD



$$\sigma[e^+e^- \to \Upsilon(2S)\pi^0\pi^0] = (1.87 \pm 0.11 \pm 0.23)\ \text{pb}$$

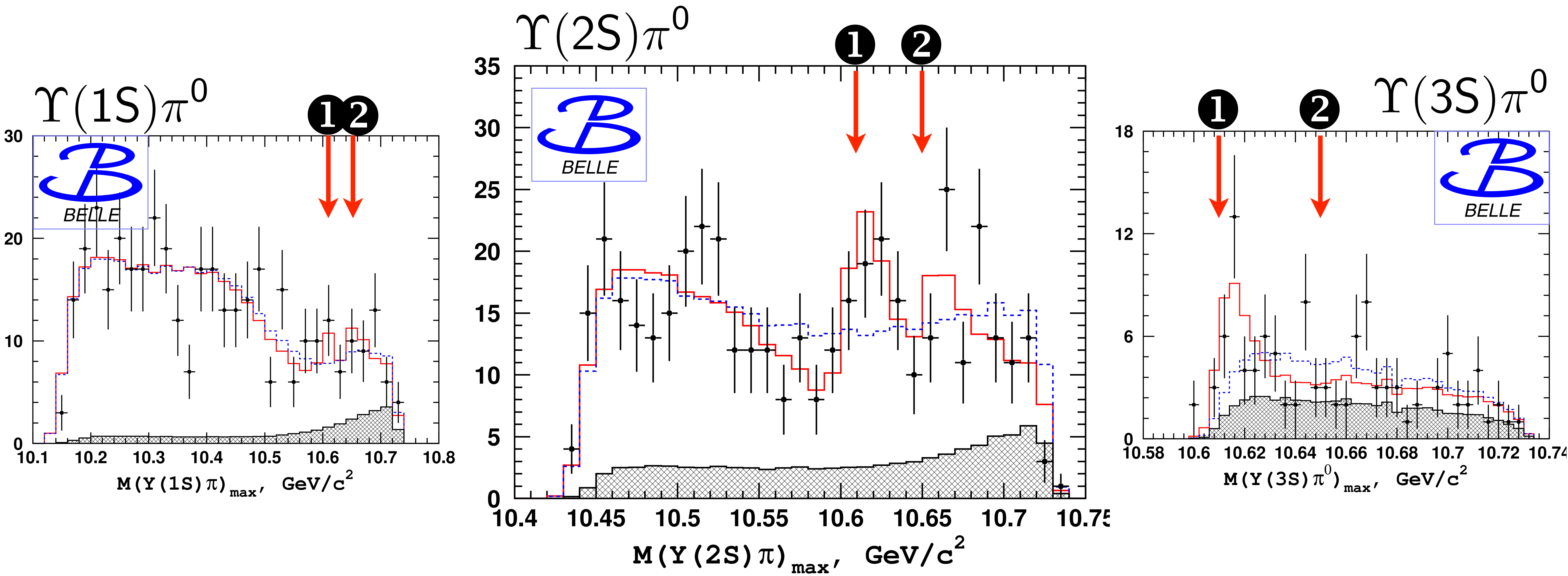
$$\sigma[e^+e^- \to \Upsilon(1S)\pi^0\pi^0] = (1.16 \pm 0.06 \pm 0.10)\ \text{pb}$$

$$\sigma[e^+e^- \to \Upsilon(3S)\pi^0\pi^0] = (0.98 \pm 0.24 \pm 0.15)\ \text{pb}$$

... consistent with half of $\sigma[e^+e^- \to \Upsilon(nS)\pi^+\pi^-]$

Select $\Upsilon(nS)$ candidates and form $\Upsilon(nS)\pi^0$ combos

arXiv: 1308.2646, submitted to PRD



$Z_b^0(16010)$: $M = (10609 \pm 4 \pm 4)$ MeV $\mathcal{S} = 6.5\sigma$

(consistent with $Z_b^{\pm}(10610)$ mass)

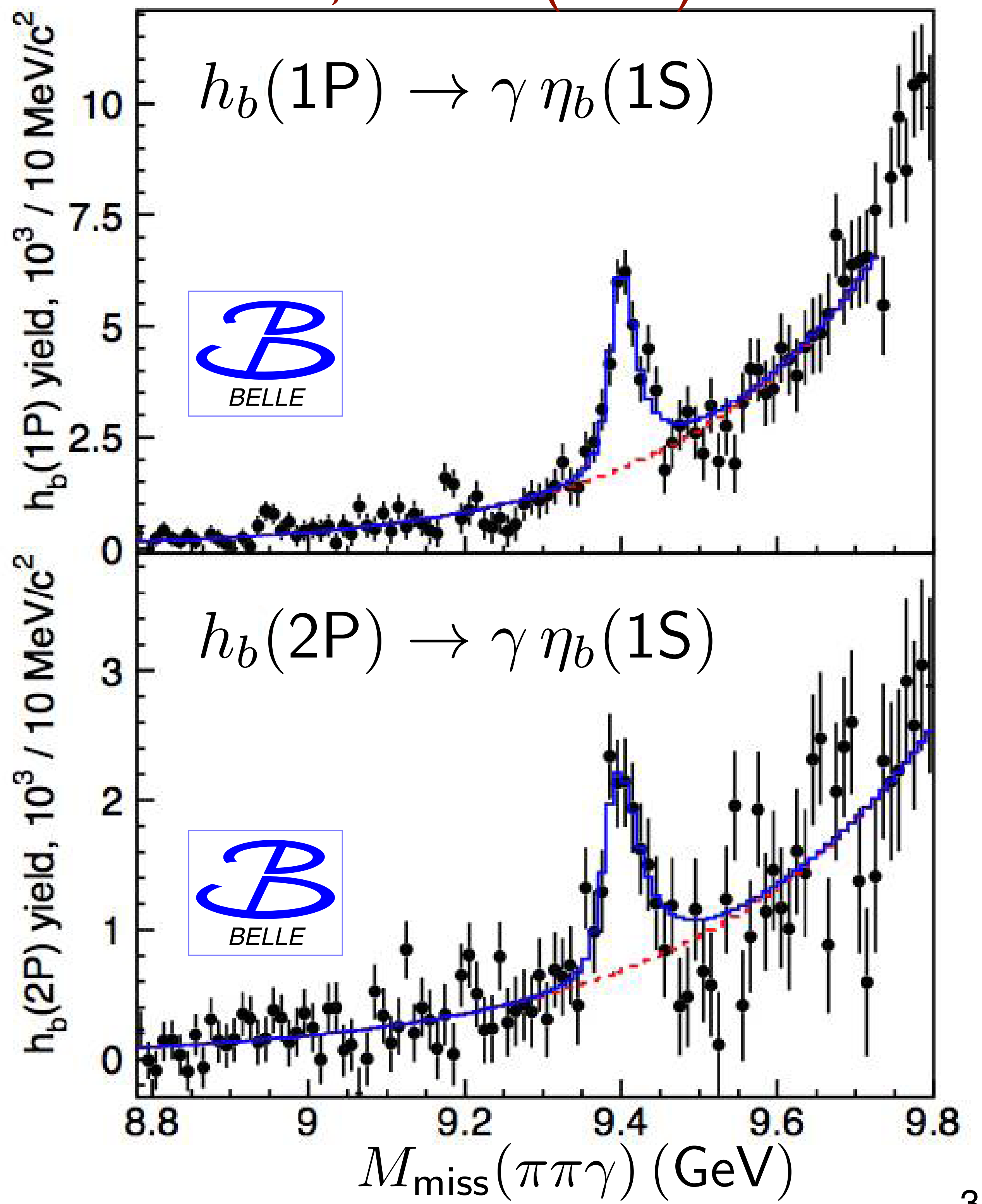
$Z_b^0(10650)$: not statistically significant

Our high yield of $h_b(\text{nP})$ lets us study the $\eta_b(\text{nS})$ states via E1 transitions $h_b(\text{nP}) \to \gamma\, \eta_b(\text{nS})$

$\eta_b(1S)$ was first seen by BABAR: PRL 101, 071801 (2008) and PRL 103, 161801 (2009)

"Rediscovered" by Belle ☛

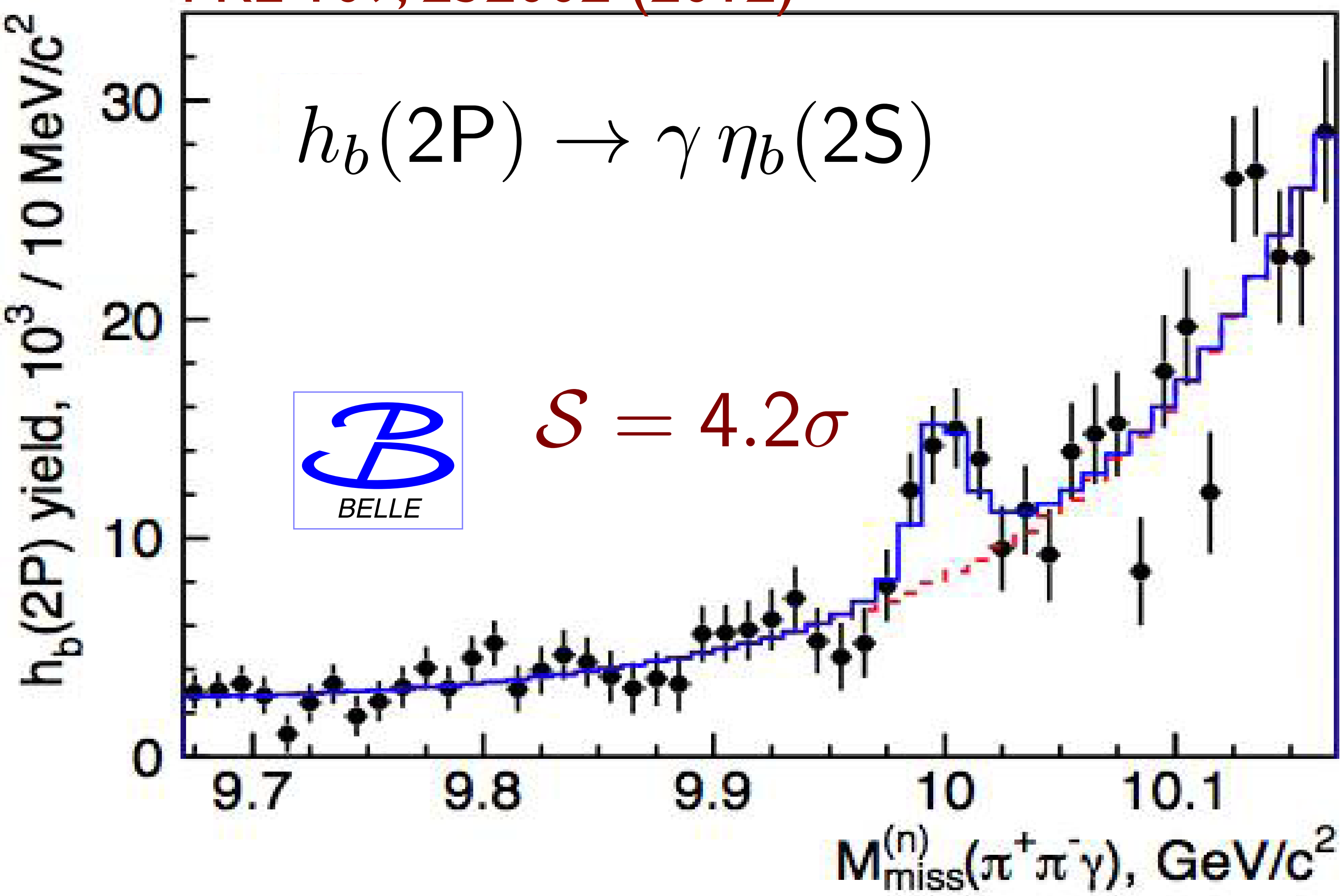
PRL 109, 232002 (2012)



Our high yield of $h_b(\text{nP})$ lets us study the $\eta_b(\text{nS})$ states via E1 transitions $h_b(\text{nP}) \to \gamma\,\eta_b(\text{nS})$

Belle sees the $\eta_b(2S)$

PRL 109, 232002 (2012)

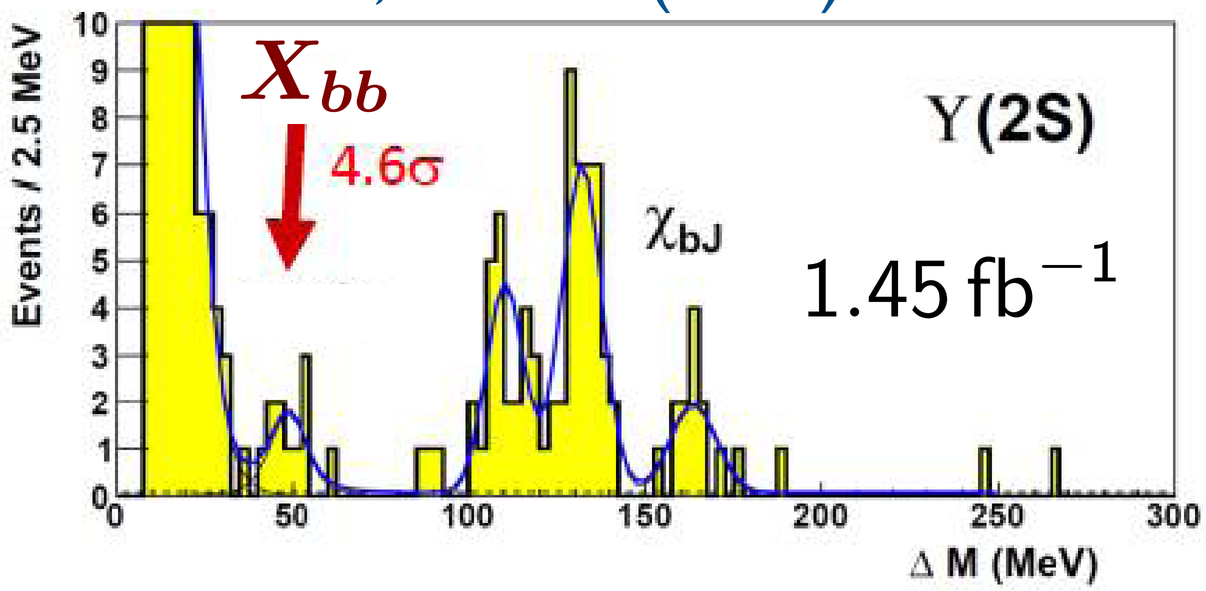


$$M_{\eta_b(2S)} = (9999.0 \pm 3.5 \pm {}^{2.8}_{1.9})\ \text{MeV}$$

$$\mathcal{B}[h_b(2P) \to \eta_b(2S)] = (47.5 \pm 10.5 \pm {}^{6.8}_{7.7})\%$$

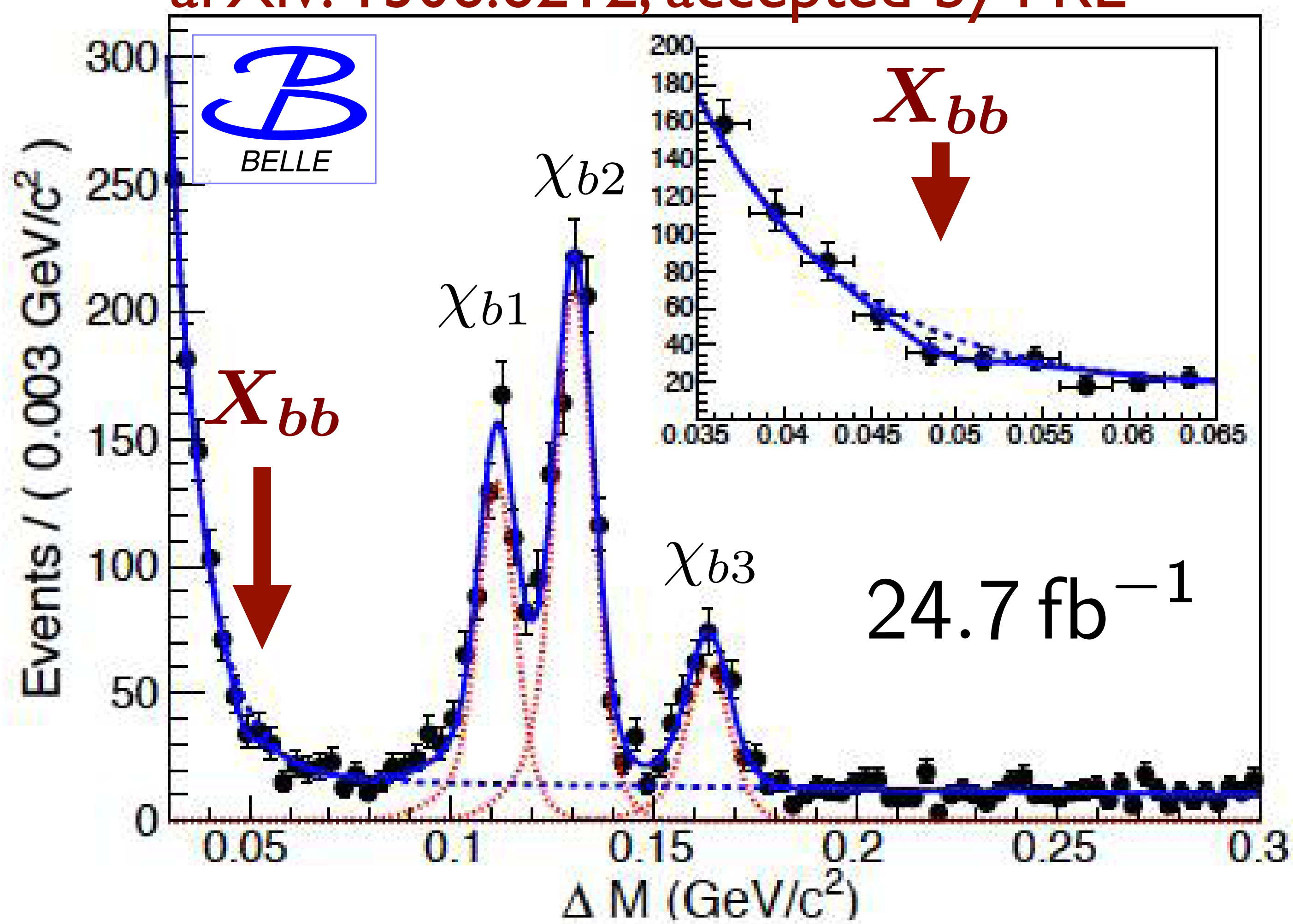
The claim of Dobbs *et al* of a new state $X_{bb}(9975)$ is inconsistent with Belle's analysis using same method

Dobbs *et al* analysis of CLEO data
PRL 109, 082001 (2012)



$M(X_{bb}) = (9974.6 \pm 2.3 \pm 2.1)$ MeV

arXiv: 1306.6212, accepted by PRL



26 hadronic final states	$\mathcal{B}[\Upsilon(2S) \to \eta_b(2S)\gamma] \cdot \sum_i \mathcal{B}_i[\eta_b(2S) \to f_i]$
Dobbs *et al*:	$(46.2 \pm ^{29.2}_{14.2} \pm 10.6) \times 10^{-6}$
Belle:	$< 4.9 \times 10^{-6}$ @ 90% CL

Summary

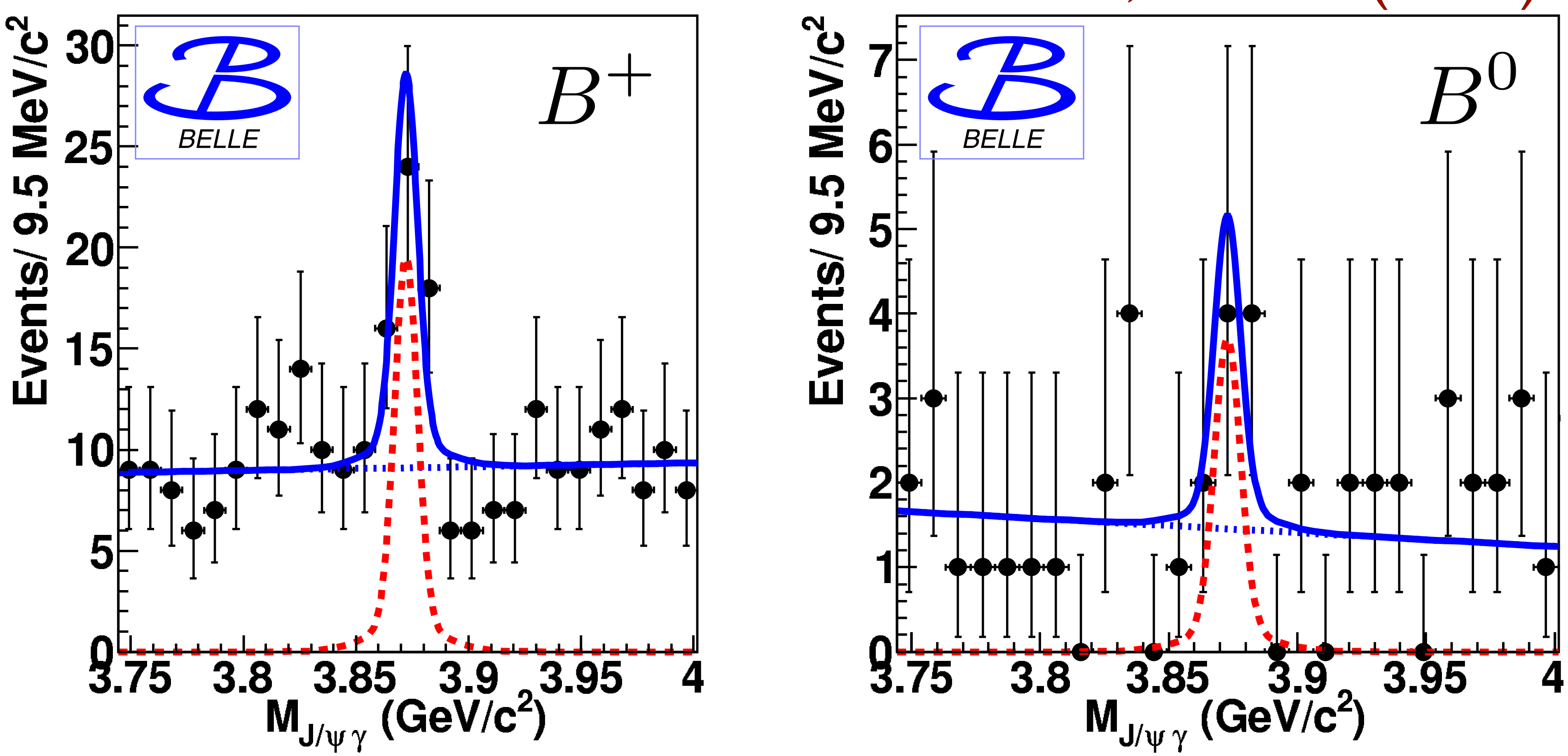
- The properties of the $X(3872)$ are consistent with a $D\bar{D}^*$ S-wave molecular state, perhaps admixed with $c\bar{c}$. Its charged and *C*-odd neutral partners are not seen.
- Charmonium ψ_2 $(=1\,^3\mathrm{D}_2)$ has been observed
- Charged charmonium-like states $Z(4430)^+$ and $Z(3900)^+$ ($|c\bar{c}u\bar{d}\rangle$) have been reaffirmed/observed
- The $\Upsilon(5S)$ decays to $h_b(\mathrm{nP})\pi\pi$ and $\Upsilon(\mathrm{nS})\pi\pi$ via one of two exotic states, $Z_b^+(10610)$ and $Z_b^+(10650)$, i.e., $|b\bar{b}u\bar{d}\rangle$, that appear to be $B^{(*)}\overline{B}^*$ S-wave molecular states at or near threshold. These $Z_b^{\pm}$ states prefer to decay to $B^{(*)}\overline{B}^*$.
- The neutral partner, $Z_b^0(16010)$, has been observed.
- The $X_{bb}(9975)$ claim by Dobbs *et al* is refuted.
- **See Peter Krizan's talk tomorrow for more Belle results.**

Backup

$X(3872) \to J/\psi\,\gamma$ determines $C = +1$ assignment

- First seen by Belle in 2005. Here, with full data set:

PRL 107, 091803 (2011)



$N = 30.0 \pm^{8.2}_{7.4}$ $\quad$ $N = 5.7 \pm^{3.5}_{2.8}$

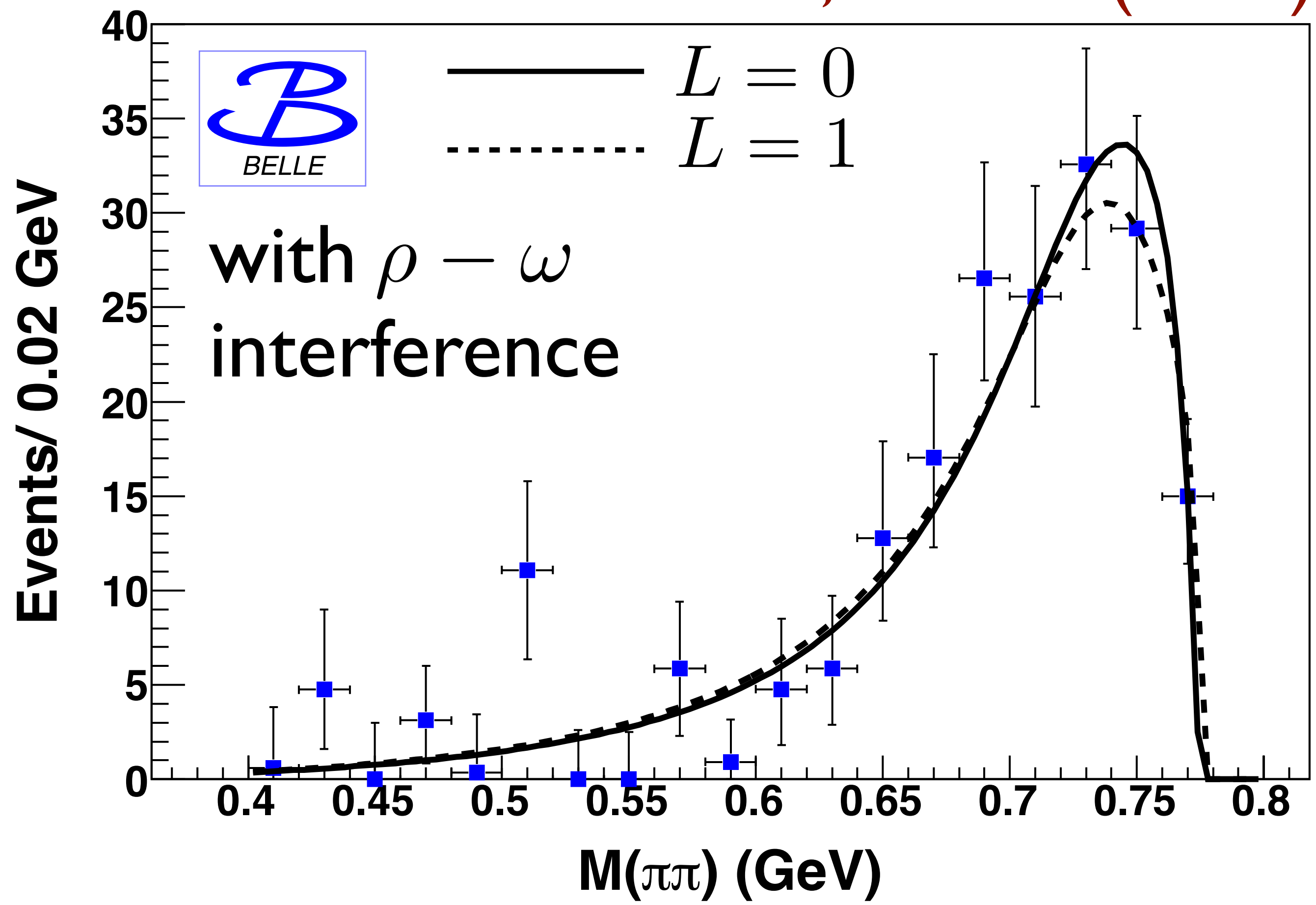
$\mathcal{S} = 4.9\sigma$ $\quad$ $\mathcal{S} = 2.4\sigma$

$$\mathcal{B}(B^+ \to K^+ X) \times \mathcal{B}(X \to J/\psi\,\gamma) = (1.8 \pm 0.5) \times 10^{-6}$$

cf BaBar $(2.8 \pm 0.8) \times 10^{-6}$ PRL 102, 132001 (2009)

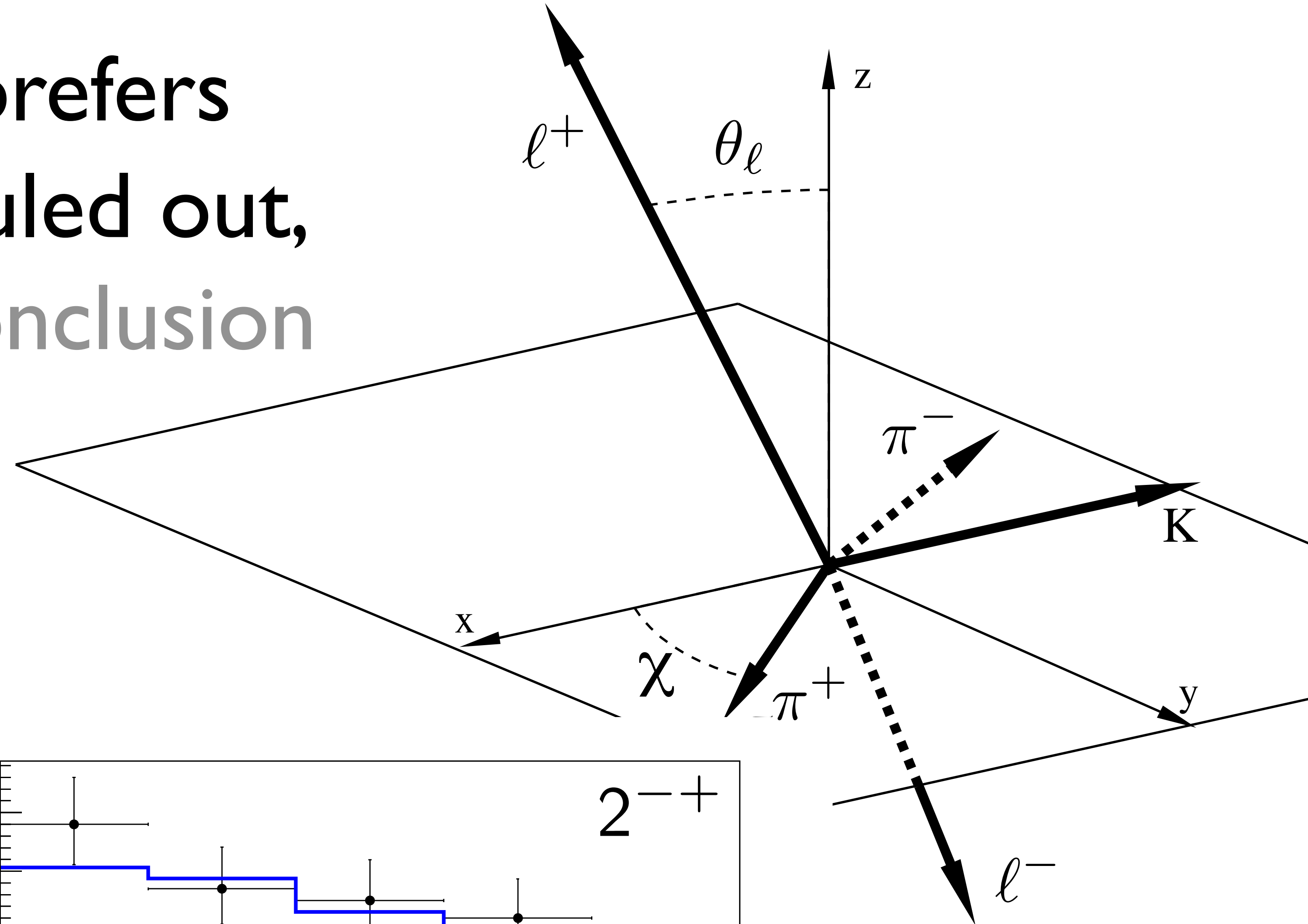
$X(3872)$ decays to $\rho\, J/\psi$: dipion mass is consistent with $\rho \to \pi^+\pi^-$; also, $C(\pi\pi) = C(X)/C(J/\psi) = -1$ matches C-parity of the ρ .

PRD 84, 052004 (2011)

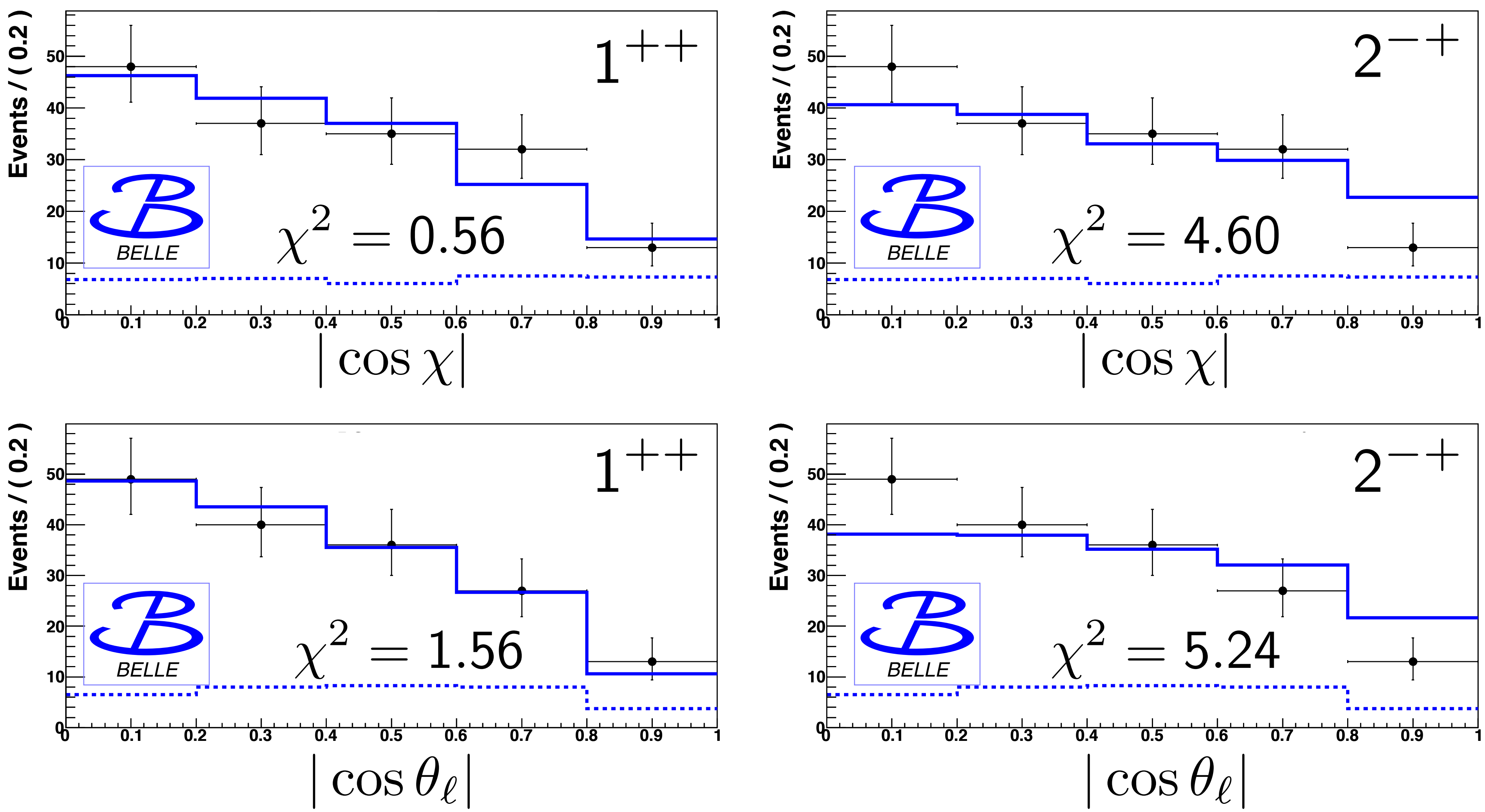


$c\bar{c} \to \rho\, J/\psi$ wouldn't conserve isospin, so this disfavors $X = c\bar{c}$ interpretation.

Belle's angular analysis prefers J^{PC} = 1^{++} but 2^{-+} not ruled out, consistent with CDF conclusion

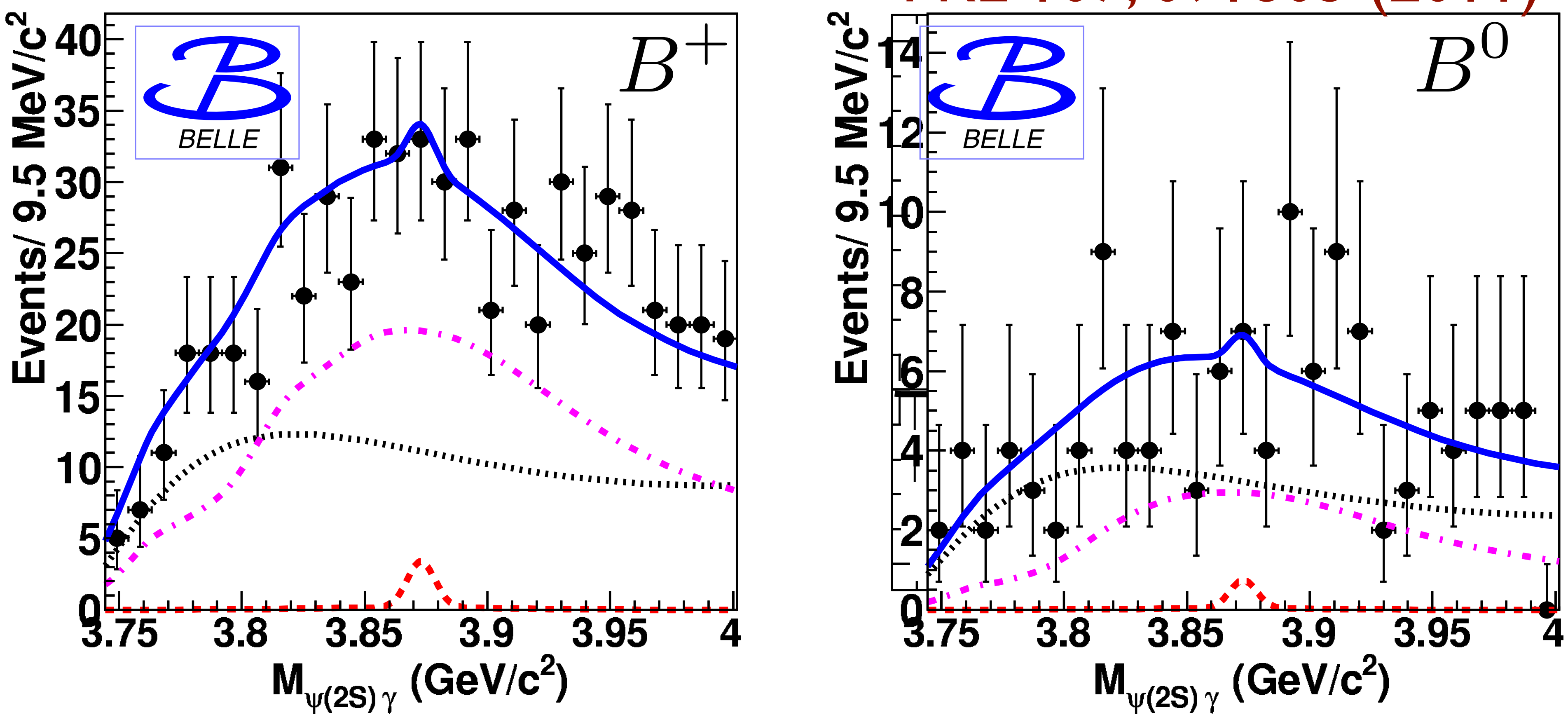


PRD 84, 052004 (2011)



$X(3872) \to \psi' \gamma$ is not seen by Belle $\Rightarrow$ admixture of $c\bar{c}$ with $D^0 \bar{D}^{*0}$ molecule is small

PRL 107, 091803 (2011)



$N = 5.0 \pm^{11.9}_{11.0}$ $\quad$ $N = 1.5 \pm^{4.8}_{3.9}$

$$\frac{\mathcal{B}(X \to \psi' \gamma)}{\mathcal{B}(X \to J/\psi \gamma)} < 2.0 \text{ @ } 90\% \text{ CL}$$

cf BaBar 3.4 ± 1.4

h_b(1,2P)

$(b\bar{b})$: S=0 L=1 $J^{PC}=1^{+-}$

Expected mass

$\approx (M\chi_{b0} + 3\ M\chi_{b1} + 5\ M\chi_{b2}) / 9$

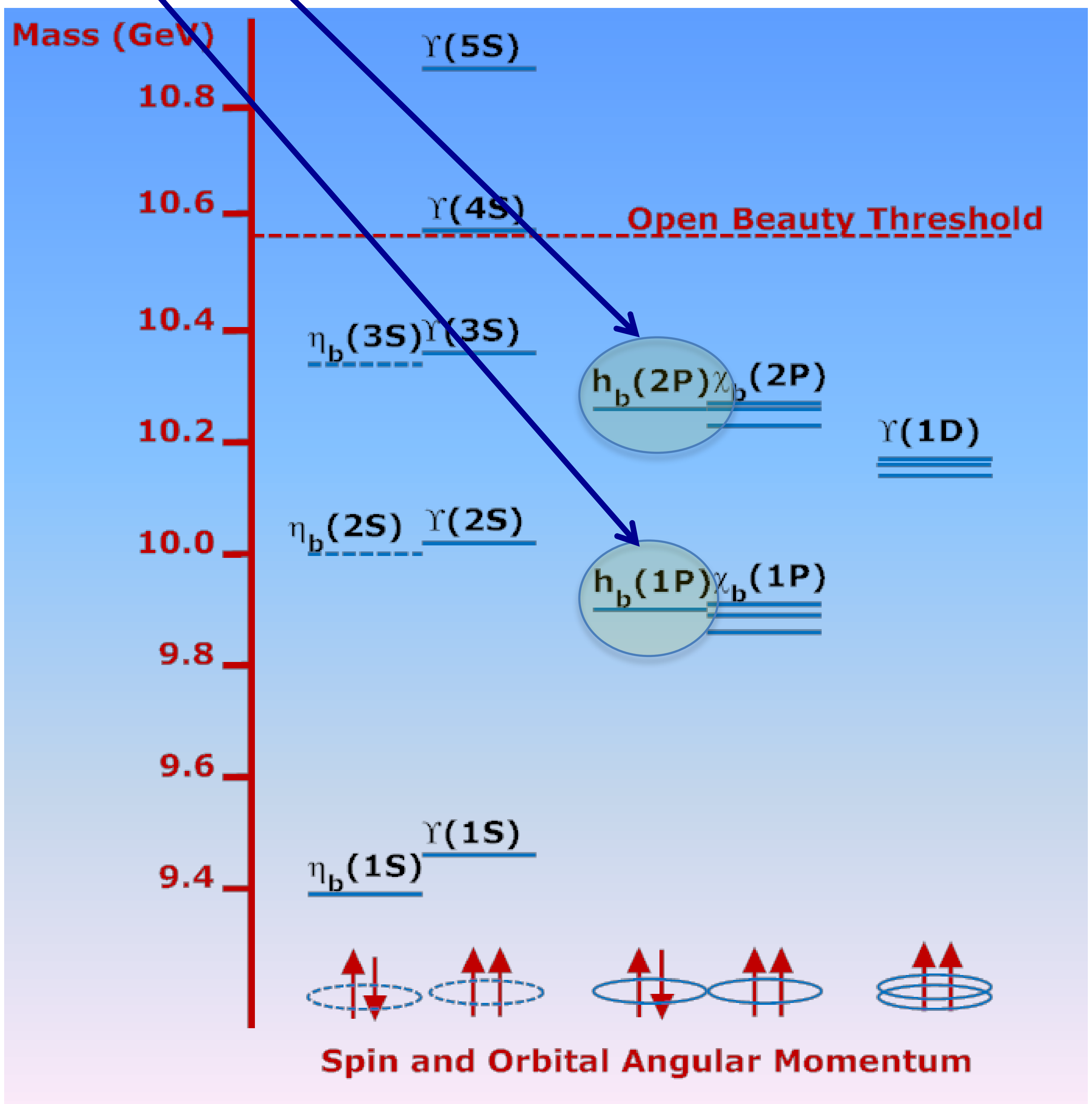
$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

Deviations from CoG of χ_{bJ} masses

h_b(1P) (1.6 ± 1.5) MeV/c^2

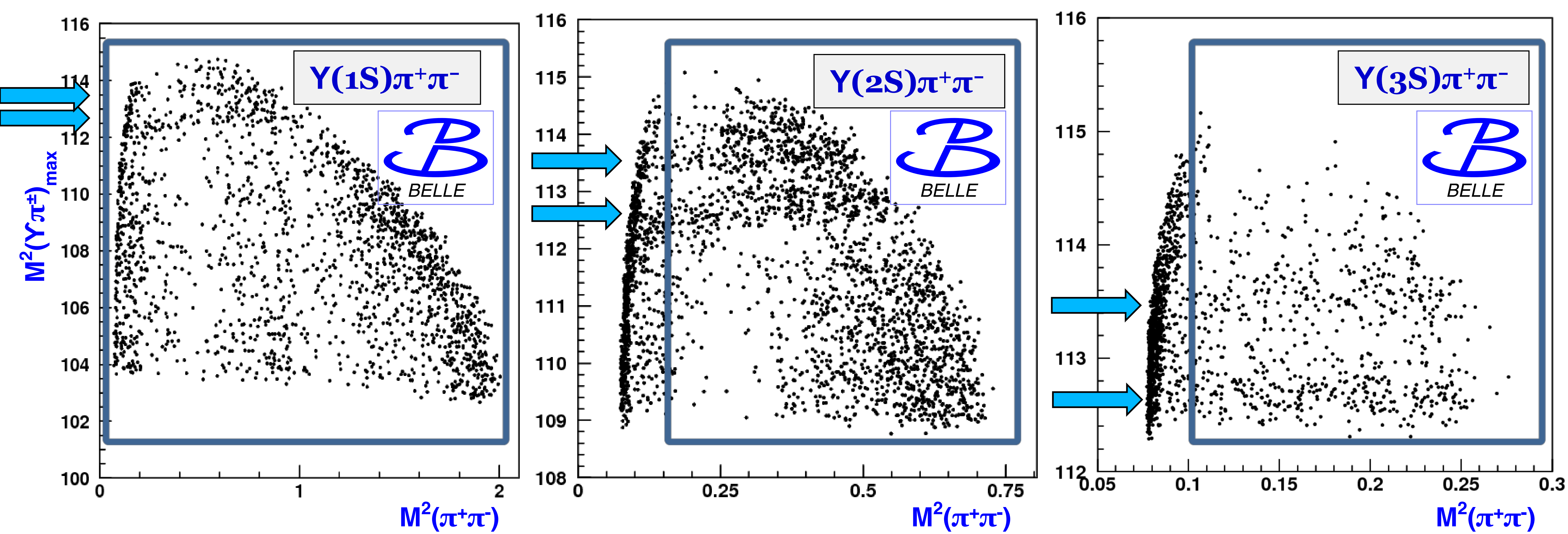
h_b(2P) $(0.5\ ^{+1.6}_{-1.2})$ MeV/c^2

Agrees with expectations



Repeat for $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$: form Dalitz distributions of $M^2(\Upsilon\pi)$ versus $M^2(\pi\pi)$, discard background, then project onto vertical axis

9.43 GeV < $MM(\pi^+\pi^-)$ < 9.48 GeV | **10.05 GeV < $MM(\pi^+\pi^-)$ < 10.10 GeV** | **10.33 GeV < $MM(\pi^+\pi^-)$ < 10.38 GeV**

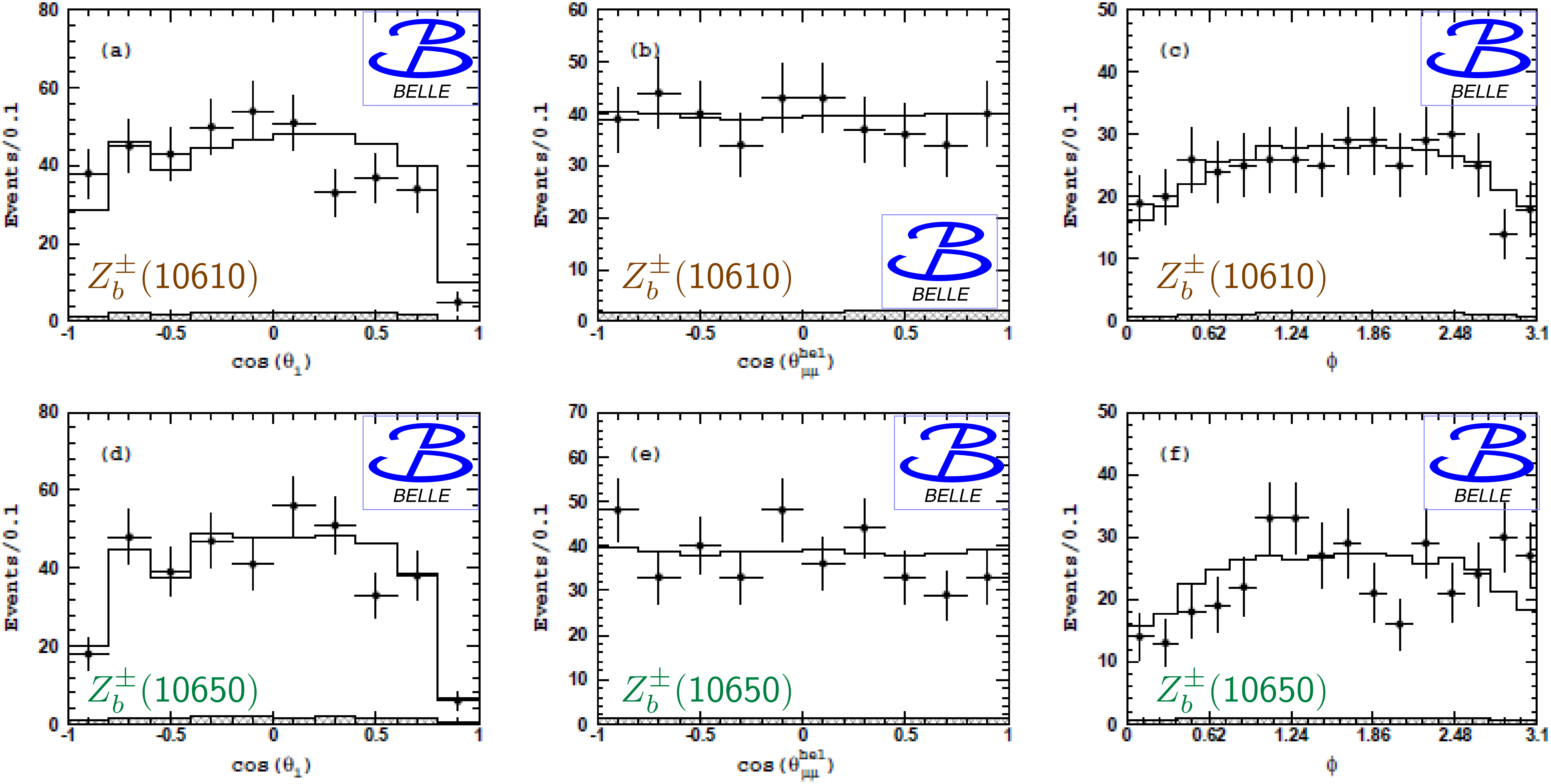


To exclude contamination from gamma conversions we require:

$M^2(\pi^+\pi^-) > 0.20$ GeV² | **$M^2(\pi^+\pi^-) > 0.16$ GeV²** | **$M^2(\pi^+\pi^-) > 0.10$ GeV²**

PRL 108, 122001 (2012)

Angular analysis prefers $J^P = 1^+$ for both $Z_b^{\pm}$ states



Angle between prompt pion and beam axis

$\Upsilon \to \mu\mu$ helicity angle

Angle between planes formed by $\pi^+\pi^-$ and Υ + beam axis

arXiv: 1105.4583